JUNE, 1955

BRAIN

VOL. 78, PART 2.

NEUROLOGICAL DEFICIENCIES AFTER ABLATION OF THE PRECENTRAL MOTOR AREA IN *MACACA MULATTA*[1]

BY

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SINCE 1869 when Hughlings Jackson (1931, p. 59) defined the cerebral cortex anterior to the central sulcus as serving "in the motor aspect of mind," many investigators have studied the frontal lobes in an effort to determine the anatomical and functional divisions of the so-called "motor" cortex.

Recent re-examination of the motor areas of the frontal lobes in the monkey has defined by electrical stimulation the two distinct somatotopically organized precentral and supplementary motor areas (Woolsey and Settlage, 1950; Woolsey *et al.*, 1950, 1952). Fig. 1 shows the localization of the areas.

Since these motor areas do not coincide with any previous definition of the "motor" cortex, it was decided to investigate the effects of placing lesions according to these maps. In this paper the results following removal of the precentral motor area will be presented; subsequent papers will describe the effects of ablation of the supplementary area and the results of lesions involving both precentral and supplementary motor areas.

METHODS

Materials

Four fully grown adult and four adolescent monkeys (*Macaca mulatta*) were subjected to precentral motor ablations. Precise lesions

[1]Research was aided by grants from the Laukhoff Trust Fund, the National Institutes of Health, and the Wisconsin Alumni Research Foundation.

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were made and these monkeys were studied in detail for typical deficiencies. We were mainly interested in the post-operative motor status of the extremities. Hence the limb motor areas were ablated sparing the face areas, since other experiments demonstrated that removal of the face area did not add any additional deficit to that of the limbs. The face areas were always damaged slightly, in order to make certain that the arm areas were entirely destroyed. The accuracy of the lesions was determined by stimulation at the time of operation, often by re-estimulation at successive operations, and by gross examination after autopsy of the animals that were sacrificed. A study of thalamocortical relations was made on these specimens (Akert, 1954). Marchi studies were done on the brain-stem and spinal cord (Barnard, 1953).

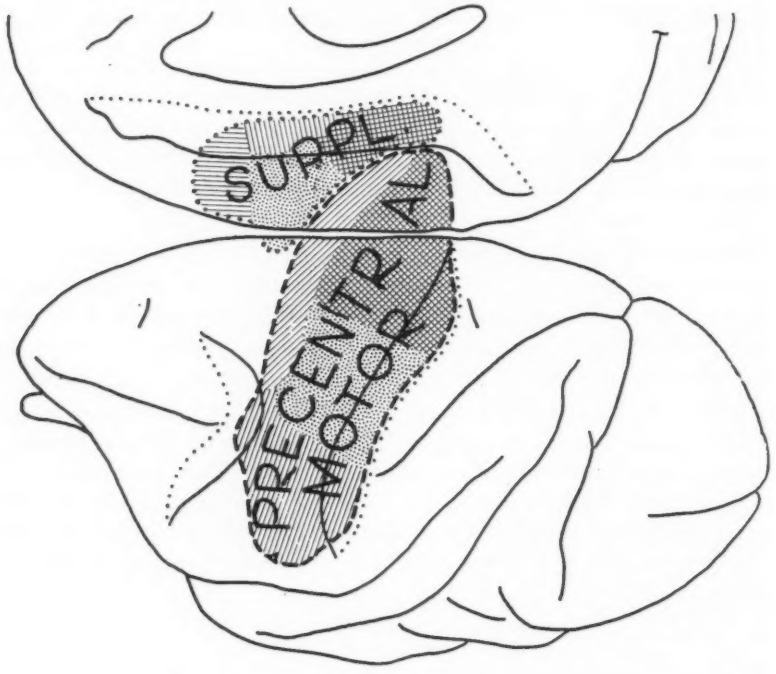

FIG. 1.—The extents of the precentral and supplementary motor areas of the monkey on the medial and dorsolateral aspects of the hemisphere. Each area is redivided into four smaller areas to represent localization of parts of the body; cross-hatching for hind-limb, dots for fore-limb, hatching most lateral in precentral motor and most anterior in supplementary area for face, and remaining two hatched areas for trunk musculature. The light dots parallel to the sulci for most of their distance designate the bottoms of the three sulci.

Surgical Procedures

All operations were performed under surgical anæsthesia induced with pentobarbital sodium given intraperitoneally. Since the validity of experimental data involving the nervous system depends upon the accuracy with which lesions are made, special attention was given to the details of surgical technique. The operations were accomplished under careful asepsis by Dr. Clinton N. Woolsey.

Usually a free bone-flap was turned, which was replaced and held in position with sutures placed through very small drill holes. The dura was so incised that its closure could be made entirely over the lesion except at the ends of the incisions. This minimized the formation of adhesions over the surrounding tissue allowing subsequent operations to be easily performed. Lesions were made with the aid of a binocular loupe, and special care was taken to preserve the chief afferent and efferent vessels to the remaining tissue.

Motor cortex ablations were performed according to the precentral and supplementary motor maps (fig. 1) but were usually preceded by cortical stimulation with monopolar type electrode (indifferent on abdomen) to delimit the exact boundaries of the lesion in each animal. The aspiration technique of cortical removal was used because it possesses definite advantages over the cautery or blunt dissection techniques. The benefits are: preservation of a clear operative field, better control of bleeding, minimal trauma to adjacent cortex, and removal of tissue inaccessible to ordinary instruments by using aspiratory tips of correct shape and size. Special precautions were taken in removing the precentral hind-limb area to avoid damaging the supplementary area, and care was taken to go only as deep as the cortex toward the white matter thus aiming to spare all fibres from the supplementary hind-limb area.

Methods of Examination

Post-operatively the animals were examined every other day for the first week and were subsequently tested at approximately weekly intervals until the time of reoperation or of death. The examining chair consisted of a wooden V back chair, which could be clamped to the side of a table, and into this each monkey was strapped leaving all limbs free for examination.

Cage behaviour, unusual patterns of walking, righting reactions, and posture assumed in the examining chair were the general observations noted. The distribution of muscle tone was examined by passive movements of the extremities and by observation of the positions

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assumed by joints distal to those moved. Tendon reflexes were examined with a rubber reflex hammer in the usual manner. Abdominal reflexes were examined by pricking lightly the skin of the abdominal wall, and plantar reflexes were elicited by stroking the plantar surfaces of the feet with a blunt instrument, beginning at the heel and proceeding to the base of the toes. The degree of atrophy following the lesions was approximately determined by taking limb measurements at seven standard positions in each fore- and hind-limb. These measurements were taken pre-operatively and then at specific intervals during the post-operative period. By calculating the cross sectional areas from the measured circumferences, the percentage of decrease at each position could be determined. The grasp reflex, more correctly termed in the monkey the "hanging reflex," was tested by determining the length of time that an animal would hold on to a bar or the examiner's index fingers with his hands or feet. The placing and hopping reactions were routinely tested.

Results

Table I lists the monkeys which had the precentral limb areas removed and gives the sequences of the operations in each animal. The results from these experiments will be summarized under major headings.

Table I.—Sequences of Operations of the Precentral Motor Limb Areas

*Animal No.**	*Name*	*Sex*	*Wt. Kg.*	*Operation No.*	*Date*	*Date of Last Observation*	*Lesions*
50–10	Peter	M	6·7	1	4.2.50		Left precentral fore-limb area.
			7·9	2	17.5.50		Right precentral fore-limb area.
			8·7	3	11.8.50		Left precentral hind-limb area.
			9·0	4	5.10.50	24.11.50	Right precentral hind-limb area.
50–70	Oscar	M	7·5	1	16.6.50	25.10.50	Bilateral precentral fore-limb area.
50–74	John L.	M	8·4	1	27.6.50		Bilateral precentral fore-limb area.
			10.0	2	30.11.50	10.8.50	Bilateral precentral hind-limb area.
51–30	Hope	F	3·7	1	28.5.51	29.6.51	Left precentral fore-limb area.

*These numbers were the laboratory serial numbers; the number before the hyphen referred to the year in which the animal was operated upon the first time. Each animal retained the same number throughout its existence in the laboratory.

General observations.—In each instance deficits were observed only in the limbs contralateral to the lesions. No ipsilateral motor deficiencies were detected. In monkeys 50–10 and 50–74 additional removal of the hind-limb areas after recovery from previous complete fore-limb area ablations yielded no additional impairment of the upper extremities. There seemed to be definite somatotopic localization of the precentral motor area, and these ablational data are contrary to the opinion that every part of the motor cortex exerts some control over all parts of the body musculature. No sensory deficit was detected in any of the animals. There was good localization to cotton stimulation.

Cage behaviour.—Brief summaries after certain operations in two monkeys will serve to illustrate the typical deficiencies.

A description of monkey 50–10 after his first operation, *ablation of the left precentral fore-limb area,* follows. A few hours post-operatively, while he lay on his right side attempting to right himself, the right fingers formed a tight fist, and this elbow flexed strongly. For five days the right fore-limb usually hung pendant, except for semiflexion of the lateral digits at the first and second interphalangeal joints. On the second day the monkey in the adjacent cage threatened him. He immediately shook his cage with the left hand and also placed his right hand in the side of the cage bending the elbow 90 degrees. The monkey in the next cage reached across and touched his right fingers. Instead of removing this hand from the cage, he seemed to hold on tighter and fought vigorously with the left hand. On the sixth day he rubbed the right side of his face with the back of the right hand, and accompanying the movement there was elevation and retraction of the shoulder with maximal flexion of the elbow. After a week, movements, such as elevating the shoulder to empty the food pouch and grasping the cage, were frequently noted in the right fore-limb. After two weeks he picked up small pieces of food by apposition of the right thumb and index finger. Manipulation of the fore-arm was accomplished to orient fingers properly to the mouth. Movements were slow but precise; the slowness constituted a permanent deficit. After three weeks slowly executed grooming movements were present in the right hand. Although he used the abnormal right upper limb, up to the time of the next operation (over three months post-operatively) it was not used as often as the left. If both hands were free, the left was preferred in taking food held directly in front of him. If food was offered from the right, generally the right hand accepted it. If a piece of food was large, however, the left hand took the food from the right and transferred it

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to the mouth. Initially only the left hand grasped a whole apple, but soon both hands held the apple. Often, however, he released the grasp of the right hand. He did not elevate the right shoulder as often as the left in emptying his food pouch, and frequently the left hand emptied the right pouch. No deficit was demonstrable in the left upper extremity or in either hind-limb.

The following observations were made on monkey 50–10 after his third operation, *removal of the left precentral hind-limb area.* No deficit was observed in the left lower extremity. On the second day the right foot did not place on the bar, but the right knee and hip flexed at right-angles in the air with ankle plantar flexed and toes extended. On the fifth day he placed this foot on the bar, but it tended to slip off after once placed. Right toes only occasionally flexed around the bar; his hind-limb assumed a flexed posture with no rotation of the thigh. His right foot was always placed secondarily to the left when he climbed upon the bar, and even after maximal recovery the right toes grasped about half as frequently as the left ones. There was no additional impairment of the upper extremities. A preference for the right hand persisted. He groomed not only himself but the monkey in the next cage, but the fingers remained slow. Although he accurately placed his fingers at the edge of his dressing, he could not remove the bandage from his head; he merely picked at it for hours.

After his first operation, *bilateral removal of the precentral fore-limb area,* monkey 50–74 showed the following findings. For a week both upper extremities remained pendant most of the time, except for slight flexion of the fingers at the metacarpophalangeal and first interphalangeal joints. On the second day he flexed his elbows and grasped the cage with both hands. On the third day he once emptied the right food pouch with the back of his right hand. In the third week his right hand transferred food to his mouth in clawlike fashion. After three months he slowly took raisins by apposition of the right pollex and index finger, and if one insisted, he used the left hand in a clawlike manner. After four months he could appose the thumb and index finger of the left hand. Both hands remained slow, and there persisted definite preference for the right hand. Often he took food with the mouth directly. The left hind-limb moved a little more slowly than the right for five days.

After a second operation, *bilateral removal of the precentral hind-limb area,* monkey 50–74 had the entire precentral limb areas ablated bilaterally. On the first day he sat on the floor of his cage and both lower limbs were flexed except for the toes which were extended. By

the fourth day he sat on his bar, placed his feet on the wires of the side of the cage, and at times flexed his toes. After a month he reached maximal recovery. He remained slow in the use of all limbs and his fingers were used in an awkward manner. Figs. 4A, B, C, and D depict postural attitudes assumed in his cage, whereas fig. 4E demonstrates an upright standing position.

Chair posture.—If the fore-limb was involved, it was placed occasionally on the arm of the chair as early as the second day. After maximal recovery the affected upper extremity did not place on the arms of the chair as constantly as in normal animals. Often the fore-limb hung pendant, but with maximal recovery the fingers usually grasped the chair. If the hind-limb area was removed the opposite lower extremity usually remained pendant with toes extended for about a month. After six weeks the involved hind-limb placed and grasped the chair part of the time. Fig. 4F of monkey 50–74 illustrates a typical posture in the examining chair after maximal recovery from bilateral precentral fore- and hind-limb area lesions. Although the tonus was difficult to distinguish from that present in a normal relaxed monkey, certain differences in posture were noted. Whereas the normal monkey places both feet constantly on the chair and holds on by flexing all toes, he only placed his feet about half the time—sometimes one, then the other, and less frequently both simultaneously. Likewise, the hands were not placed on the arms of the chair as constantly as in normal animals. He often assumed a normal posture, but it was not continually maintained.

Tonus.—An immediate hypotonia occurred in the extremities contralateral to the precentral lesions. The limbs, however, were never completely limp. For about a week the fingers of the affected hand assumed semi-flexed postures and after passive extension resumed this position like weak springs. Gradually approximately normal tonus became present, and no permanent hypertonia resulted from the precentral motor lesion.

Tendon reflexes.—Initially the tendon reflexes were less active in the affected limb than observed in the normal extremities. The triceps and finger jerks, usually within two weeks, entered a moderate hyperactive phase, without clonus, lasting five to seven months. Biceps-jerk was difficult to obtain in these animals. The reflexes of the lower extremities gradually returned to normal with generally no period of hyperactivity.

Abdominal reflexes.—After removal of the abdominal representations, the reflexes opposite the lesion were absent for two weeks. The

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reflexes were impaired for an additional two to four weeks, after which interval the abdominal reflexes appeared normally active.

Plantar reflexes.—The plantar reflex, in the foot opposite the precentral hind-limb area ablation, showed a permanent motor deficit. The normal plantar response usually initially consists of extension of the toes and dorsiflexion of the ankle as one begins stroking the heel, and as the stimulus proceeds to the base of the toes, there follows flexion of the toes, inversion of the foot, and frequently flexion of the knee and thigh in a withdrawal response. Initially after the precentral hind-limb lesion only slight twitching and apposition of the first and second toes was observed. Within two to four weeks the reflex reached maximal recovery and consisted of apposition of all toes. The withdrawal response involving the entire lower extremity seldom accompanied these reactions; instead the hand reached down to remove the stimulus.

Pupils.—In monkey 50–10 after the first operation the left pupil was 0·5–1·0 mm. larger than the right for ten days. After his second operation the left pupil measured 4 mm. in diameter while the right was 3 mm., but after two weeks pupils were equal. In each instance after the other operations on these monkeys the pupils were equal.

Atrophy.—Standard measurements in the fore-limb were taken: just beneath the belly of the deltoid muscle or over the greater mass of the triceps; over the largest portion of the biceps; above the elbow; below the elbow; wrist; and at the level of the metacarpal bones, with and without the pollex. In the hind-limb measurements taken were: thigh

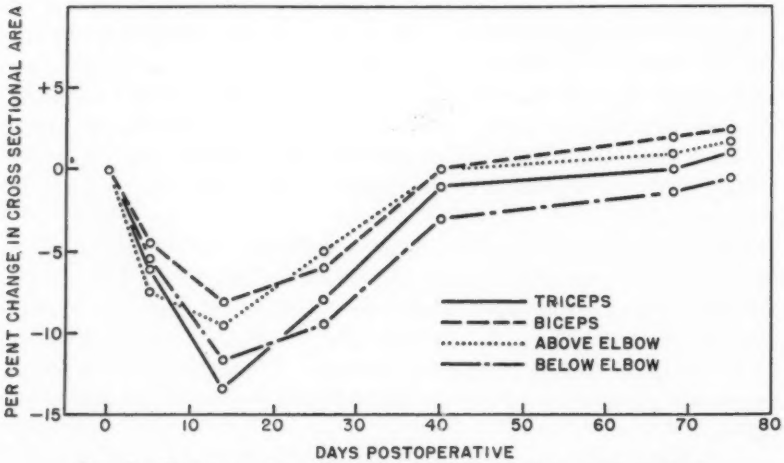

FIG. 2.—Post-operative atrophy of right fore-limb in monkey 50–10 after first operation.

at level of symphysis; above knee, below knee; over the largest bulk of the calf muscles; ankle; and at the level of the metatarsal bones, with and without the hallux. Atrophy occurred in the contralateral extremity after a precentral limb area lesion. It correlated with the impaired function of the limb and reached a maximum of about 10 per cent after two to four weeks but subsided after five to six weeks. The four positions showing significant decrease in cross sectional area for monkey 50–10 following his first operation of removal of the left precentral forelimb area are plotted in fig. 2. Fig. 3 is illustrative of atrophy of the

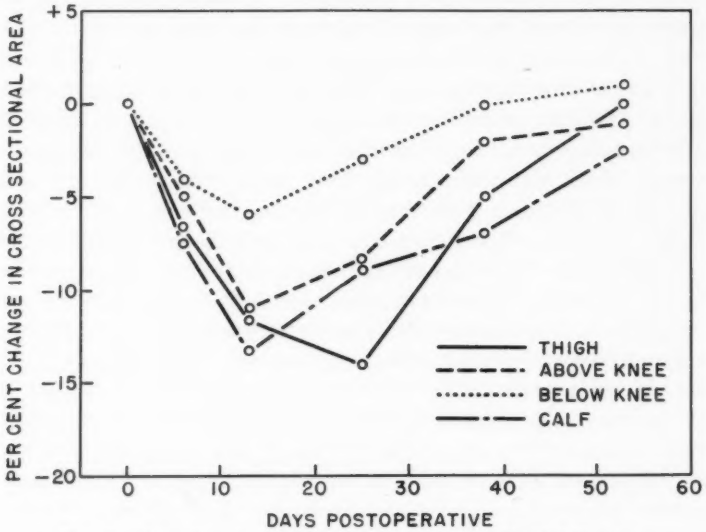

FIG. 3.—Atrophy of right hind-limb in monkey 50–10 following his third operation.

hind-limb and shows the four positions demonstrating significant changes in monkey 50–10 following the third operation of ablation of the left precentral hind-limb area.

Grasp reflexes.—The hanging reflexes were absent in these animals following each operation with one exception. In monkey 50–74 there were grasp reflexes present in the hands after his second operation, bilateral removal of the precentral hind-limb area. The right hand had a grasp lasting five seconds, while the left involuntarily grasped six to seven seconds. The reflexes persisted until the time of the next operation and were most likely due to minimal damage to the supplementary finger areas.

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Placing and hopping.—Initially following either unilateral or bilateral lesions of the precentral limb areas, placing and hopping reactions were absent in the extremities contralateral to the limb areas ablated. If an adjacent limb area was damaged, there also occurred temporary impairment of the reactions in the involved extremity. Within one to three weeks after removal of a precentral limb area, placing and hopping were present in the abnormal limb. The reactions were permanently hypermetric with a larger displacement than normal required to initiate a response. Hopping was performed faster forward and laterally than medially and backward. Hopping and placing were accurately performed but were *slower* and *less delicate* than normal, throughout the post-operative interval. Often the digits of the involved upper or lower extremity fanned. The hind-limb frequently hopped in a steppage-like gait, and often the toes flexed at right-angles at the first interphalangeal joints. Excitement of the animal always enhanced the responses. After maximal recovery from his second operation monkey 50–74 hopped forward with the hind-limbs and left fore-limbs 6–8 per meter, while the right upper extremity usually made 9–10 hops for the same distance. Normal monkeys usually hop 12–15 steps per meter.

Verification of lesions.—In five succeeding operations monkey 50–10 was completely decorticated and the precentral lesions were verified. From gross inspection and stimulation of the cortex adjacent to the lesions, no representation for the fore- or hind-limb was found. In animal 50–70 the precentral hind-limb area and part of the supplementary area were removed bilaterally at a second operation. From inspection and stimulation, the precentral fore-limb area lesions were as intended. In monkey 50–74 upon removal of the parietal lobes at two successive operations, data were obtained to account for the difference in performance of the hands. On the left near the bottom of and limited to the wall of the central sulcus was found a small strip of cortical tissue belonging to the precentral fore-limb area, which yielded fore-limb movements upon stimulation. It was 10 mm. in its mediolateral extent and 3 mm. in the ventrodorsal direction. All the left precentral hind-limb area had been removed, and on the right the lesions were complete. In animal 51–30 the ablation was determined to be complete from gross inspection of the lesion at autopsy.

Simultaneous with the observations of the neurological disturbances Hamuy (1951) studied retention and performance of skilled movements in these animals. One test was concerned with the ability of the monkey to catch peanuts as they rolled down an inclined plane, which was partitioned into 3 alleys 15 inches long, whose slope could be adjusted.

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The animal did not know before any trial in which alley the peanut would be placed, and he was required to catch each peanut by the time it reached the bottom of the slide, or it fell out of reach. At the lowest angle at which the inclined plane could be set the animals were able to catch only approximately 25 per cent of the number which a normal animal could pick up, and failed entirely when the angle was increased, although normal animals still succeed.

To supplement Hamuy's results a simple test was devised to evaluate the speed of these monkeys when objects of food remained stationary. On a clipboard raisins were arranged checker-board style, and these were always presented in front of the animal at approximately the same level as the height of the arms of the examining chair. Fig. 5 shows such a testing arrangement. Raisins were selected because they demonstrated fine movements of the fingers. Usually between 20 and 40 raisins were placed on the board; the best number was arrived at after many trials. Too many caused the animal to stop at intervals to chew up a mouthful; too few did not give an accurate representation due to initial time loss in starting. The time it took the animal to pick up the raisins was recorded by a watch with a second hand. One hand at a time was strapped behind the animal to obtain values for each hand. This test was run on many normal monkeys, and they averaged 0·5 to 0·7 second for each raisin. These animals, after complete removal of the precentral fore-limb area averaged from 1·4 to 1·7 seconds per raisin, having *approximately half* the speed of normals. No additional deficit was observed in the fore-limbs after the precentral hind-limb area lesions.

Since ablation of a complete precentral limb area resulted in no significant spasticity in the contralateral affected limb, additional experiments were performed to determine if small lesions in one of the precentral limb areas would produce hypertonia. The fore-limb area was chosen because with its removal there is less possibility of damaging the supplementary motor area than with ablation of the precentral hind-limb area.

In three animals, 50–65, 51–42, 51–61, similar small unilateral removals were made in the hand–finger area. Fig. 6 shows the extent of the lesion in monkey 51–42. The first two monkeys were kept for four weeks and the third for six weeks before autopsies were performed. Little abnormality was detected in the animals, and after recovery from the anæsthetic the hand contralateral to the lesion was used almost as well as the normal hand. In 50–65 and 51–42 the triceps and finger jerks on the side opposite the operation were hyperactive within two days and continued so throughout the survival periods, and in 51–61 the

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tendon reflexes were essentially the same as pre-operatively. No increased resistance to passive movements developed.

A fourth experiment in monkey 51–44 (20.7.51; male; wt. 8·1 kg.; Nick) consisted of bilateral removal of Hines' "strip" area rostal to the precentral hand area. On the first day little abnormality in cage behaviour was observed. Tonus was approximately normal, and no increased resistance developed. No abnormal posture such as elevation of the shoulders resulted. Tendon reflexes were difficult to obtain, as they had been pre-operatively. For a week there was slowness in the hopping reactions of the upper extremities on forward and lateral displacements. Also the placing responses were slowly performed when the backs of the hands were touched. This indicated impairments in protraction and abduction of the shoulders. After eight months his shoulders were not used as frequently as normal to empty his food pouches, but often the hands were used instead.

These experiments demonstrate that *lesions restricted to the precentral motor area, regardless of their size, produce no significant increased resistance to passive movement of the extremities.*

Discussion

Since the precentral motor area differs from previous definitions of the "motor" area, an attempt will be made to relate these results to currently accepted data on ablation derived from removals of the histologically mapped "motor" (area 4) and "premotor" (area 6) areas. First a résumé will be given of the extent of the precentral motor field in relation to the cytoarchitectural maps of Brodmann and the Vogts by which former experimental lesions were placed. The anterior boundary of Brodmann's (1909) original map of area 4 in the monkey appears to correspond closely with the rostral boundary of our precentral area. The rostral boundary of the Vogts' (1919) area 4, on the other hand, is situated more posteriorly, and the precentral motor field includes (in addition to) their areas 4*a*, 4*b*, and 4*c*, and probably their entire 6$a\alpha$ on the dorsal and lateral surfaces of the hemisphere. Likewise, the part of 6$a\alpha$ on the medial aspect of the hemisphere from which movements of the vertebral column, tail, and anus were obtained, belongs to the precentral area. The posterior boundary of the precentral field is the bottom of the central sulcus and agrees with the boundary of area 4 as described by both authors. Medially the precentral area extends only to the dorsal lip of the sulcus cinguli. Previous ablations, however, involving the "motor" hind-limb areas continued to the bottom of the

cingulate sulcus and removed the supplementary as well as the precentral hind-limb representations.

After a precentral ablation an immediate hypotonia and impairment of voluntary movements resulted in the contralateral limbs. Fulton and Kennard (1934; Kennard and Fulton, 1933) reported similar results and obtained flaccid paresis in the affected extremities after extirpation of Vogt's area 4. Hines (1937) after removal of area 4 posterior to the strip area, likewise, found immediately a rather complete paralysis with hypotonia. Our results, obtaining essentially no increased resistance to passive movement, are consistent with those of Tower (1940) who produced hypotonic paresis by section of the medullary pyramids. Since this paresis was greater than we observed in our animals, it might be attributed to interruption of fibres originating not only from the precentral but from other areas of the cortex.

Following a precentral lesion the hypotonia merged gradually into a state of approximately normal tonus. Similar results were described by Fulton and his collaborators (Fulton and Kennard, 1934; Fulton, 1935; Fulton and Jacobsen, 1935; Fulton and Viets, 1935) after removals of Vogt's area 4 and by Hines (1937) after lesions in the posterior part of Brodmann's area 4. After ablation of the precentral representations for trunk and extremities, movements recurred as soon in the distal as in the proximal joints. Differences in the results found by previous workers seems to be associated with their definition of the anterior boundary of area 4. Since Vogt's area 4 includes little of the precentral representations for the proximal limbs, Fulton and Kennard (1934) obtained greater paralysis of the distal joints with ablation of area 4 probably because mainly centres for distal joints were removed. The proximal centres were excised when Fulton and his colleagues ablated the "premotor" area. Hines (1937) after removal of Brodmann's area 4 found that the opposite limbs did not initiate independent movements but only followed movements of the normal extremities. She probably obtained greater paralysis than we did because of some involvement of the supplementary motor area.

A possible reason why finer movements of the fingers returned after a precentral fore-limb ablation, and not after lesions of Vogt's area 4, may be related to the surgical methods employed. With careful use of the suction method injury to the surrounding cortex is minimal. Formerly cortical operations were performed by blunt dissection or with the electrical cautery and either method could easily damage adjacent cortex. With removal of area 4 by cautery, damage could have occurred to the adjacent postcentral digital area. After long-standing bilateral

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ablation in adult monkeys of the precentral and supplementary motor areas, we found that isolated movements of the digits occur upon stimulation of the digital area of the postcentral gyrus (Woolsey *et al.*, 1952). Furthermore, our results after ablation demonstrated that this *postcentral motor system contributes significantly to motor function after complete precentral lesions* (Travis and Woolsey, 1953). Additional removal of the parietal lobes after a previous bilateral precentral motor lesion produced a much more incapacitated preparation. After many months the animal was still unable to feed himself with his hands. These experiments indicate a possible explanation of why the observation that finer movements of the digits recur, may disagree with those of previous authors. By closely checking with electrical stimulation we attempted to make sure that the entire precentral fore-limb area was removed.

Since fine movements of the fingers returned after removal of the precentral fore-limb area, means of determining the persisting deficits were devised. The impairment of ability to make fast adjusting movements was clearly demonstrated in the peanut slide test used by Hamuy. The method of timing the rate at which small stationary objects of food, such as raisins, could be picked up from a board was a simple but useful test in analysing continuous movement for several minutes, for most of the animals were co-operative. The animals demonstrated *approximately half* the speed of a normal monkey when no time limit was imposed upon them.

The hopping and placing reactions served as another means of studying permanent impairments. The responses were performed in a retarded, hypermetric manner and the reactions improved with excitement. After ablation of the precentral area the best hopping responses occurred upon forward and lateral displacements. Thus it seems that these two hopping reactions are less dependent upon the precentral motor cortex than is hopping in other directions. Woolsey and Bard (1936) localized the cortical areas which controlled the placing and hopping reactions in *Macaca mulatta*. They determined that unilateral ablation of Brodmann's area 4 produced enduring loss of the contralateral reactions, except labyrinthine and visual placing which became only deficient. Since the authors stated that less extensive lesions of area 4 produced only permanent deficiencies, it seems evident, in view of our results, that removal of Brodmann's area 4 included in addition to the precentral field the entire supplementary limb areas. The fact that defective hopping and placing reactions are still present after unilateral and bilateral precentral lesions indicates that the supplementary

area likewise plays an important part in the control of these postural reflexes.

Just as stimulation of the precentral field yielded movements in the contralateral limbs, the motor disturbances after removal of this area were present only in the limbs opposite the lesion. Leyton and Sherrington (1917), experimenting on chimpanzees, orang-utans, and gorillas, found that ablations of the arm area of the second hemisphere causes no added paresis of the ipsilateral arm. Bucy and Fulton (Bucy, 1933; Bucy and Fulton, 1933), however, evoked ipsilateral responses in monkeys by stimulating a restricted area about the superior precentral sulcus. The level of anæsthesia may explain why we observed no ipsilateral limb movements upon stimulation of the precentral motor area. From their ablational results Bucy and Fulton also concluded that an ipsilateral motor area existed in monkeys. This was based on the findings that an animal with bilateral removal of areas 4 and 6 was totally incapacitated, whereas if either area 4 or 6 was left intact in one hemisphere the animal was capable of moving all extremities. We have reported, however, that adult monkeys can walk, climb, and feed themselves after bilateral ablation of areas 4 and 6 (Travis and Woolsey, 1952).

Although our precentral area lesions included the "ipsilateral area" about the superior precentral sulcus, no observable ipsilateral deficits resulted. This does not prove that an ipsilateral area does not exist; it only indicates that if ipsilateral representations are present, their functions are probably small.

In these ablations involving the precentral motor cortex, we did not confirm the findings of Ades and Raab (1946), who reported bilateral compensation after unilateral lesions of area 4 such that if area 4 of the remaining hemisphere is removed after a suitable delay (three to four months) none of the signs of pyramidal injury appear. Although this time interval was allowed to elapse in early experiments, the contralateral paralysis following the second lesion was as severe as in the limbs opposite the primary ablation.

If the precentral fore-limb area was removed completely at an initial operation and the contralateral upper extremity was permitted to reach its maximal recovery, ablation of the hind-limb area on the same side as the original lesion yielded no additional impairment in the upper extremity. Thus these observations lend no support to the view that all parts of the motor cortex exert *some* control over all parts of the body musculature. Similar results were obtained by Leyton and Sherrington (1917, p. 207) who stated "neither the ablation nor excitation methods

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gave any evidence that the remaining part of the arm area had taken on the functions of the ablated hand area." Recently Glees and Cole (1950) concluded from small subsequent motor lesions that remaining adjacent cortical areas developed the ability to control the functions of previously ablated tissue. Since the authors did not remove, even at their first operation, all of the thumb area as judged by our motor map, it is not surprising that thumb movements were obtained later upon restimulation of the adjacent cortex. One would expect an additional deficit on removing this surrounding tissue. After small area 4 lesions, their animals did not reach their pre-operative skill, indicating a deficit from small removals. Our results suggest that if the thumb representations were entirely ablated at a primary operation the permanent impairment in the thumb should be as great as if the complete precentral motor area were removed. Kennard (1942) from experimental data and Bucy (1949) from clinical cases concluded that ablation of the arm area alone had less effect on arm function than if arm and leg areas were both removed. *These results were probably due to either incomplete removal of the precentral fore-limb area or involvement of the supplementary fore-limb area upon ablation of the precentral hind-limb.*

The complete inability to obtain any permanent hypertonia was an important finding. However, post-operatively certain reflexes were temporarily hyperactive though not clonic. Fulton and Viets (1935) reported after motor area ablations in monkeys that some of the reflexes (knee and biceps jerk) became hyperactive although the limbs remained flaccid. Following a lesion of the precentral fore-limb area usually a semiflexion of the fingers occurred for approximately a week following the operation, and the digits returned to this flexed posture after passive extension. Since springlike action of the fingers is observed in normal anæsthetized animals, this posture is considered normal in a state of great voluntary impairment. Under some definitions of spasticity, the temporary increased tendon reflexes and flexor posture of the fingers would probably be included. However, the degree of this transient spasticity was slight and most unimpressive in comparison with the strong results obtained after other lesions, so the conclusion that spasticity does not appear to be an effect of ablating the precentral motor area alone is not significantly altered.

The atrophy resulting in this series of experiments supports the disuse theory. The correlation between impairment of motor function and the time of greatest atrophy was close, and with the return of volitional movements the atrophy disappeared. Fulton (1936), after removing area 4 in chimpanzees, obtained an atrophy of over 50

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per cent. This is larger than we obtained in monkeys after precentral lesions perhaps because Fulton, with ablation of area 4, probably removed part of the supplementary area. Alternatively there may be a considerable species difference.

Richter and Hines (1934) produced a transient hanging reflex by unilateral or bilateral lesion of upper area 6. Since ablations restricted to the precentral motor area yielded no grasp reflex, one can assume that removal of portions of area 6 not included in the precentral motor area may be responsible for producing an involuntary grasp.

In summary, it was our goal to determine the maximal recovery obtainable in these animals, and from the impairments that remained to define the deficits characteristic of a precentral motor area lesion. In Hughlings Jackson's writings is found the following statement concerning recovery of function (1931, p. 149): ". . . it will be inferred that recovery follows not because other units take on duties they never had before; but because these units having in health closely similar duties to those of the unit destroyed, they can act nearly as well for the duties of both." After maximal recovery the functional deficits which persist can be attributed to the area destroyed. Recovery may be nearly complete, but in the words of Marion Hines (1929, p. 484), "In just that difference between complete and 'practically' complete lies the material for the final analysis of the function of the motor cortex."

Summary

These experiments were concerned with a reinvestigation of the function of the "motor" cortex studied in eight *Macaca mulatta*. Since the precentral motor area was defined as a functional unit that does not coincide with previous definitions of the "motor" cortex (Woolsey and Settlage, 1950; Woolsey *et al.*, 1952), this study was undertaken to determine the results of ablation of this area alone. The following conclusions were reached.

(1) Precentral motor area lesions resulted in immediate severe voluntary impairment, hypotonia and diminished tendon reflexes in the extremities contralateral to the ablations; no ipsilateral deficits were observed.

(2) Partial recovery of motor performance followed, and movements reappeared as soon at distal as at proximal joints; detectable impairments persisted at both.

(3) Within two to twelve weeks the animals were able to pick up small stationary objects by apposition of thumb and index finger, but

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after maximal recovery this manœuvre was accomplished with only approximately half normal speed.

(4) No significant spasticity developed. In the arms the triceps and finger jerks passed through a transient phase of moderate hyperactivity.

(5) Placing and hopping reactions returned after one to three weeks in the affected limbs, but they were performed persistently in a retarded, hypermetric manner. The responses were enhanced with excitement of the animal.

(6) The abdominal reflexes on the side contralateral to the lesion were diminished for four to six weeks following the operation, but after this interval they appeared as active as normal.

(7) The plantar reflex consisted of apposition of all toes instead of the normal active flexion of the toes and frequent withdrawal of the entire hind-limb.

(8) Atrophy of about 10 per cent appeared in the limbs opposite the lesion during the period of greatest disuse and completely subsided after maximal recovery of motor function was achieved.

(9) No grasp reflexes were obtained, although the lesions included Vogt's dorsal and part of the medial area $6a\alpha$.

(10) These experiments do not support the concept that all parts of the motor cortex exert *some* control over all parts of the body musculature.

Acknowledgments

Grateful acknowledgments are made to Drs. E. M. Larsen and D. R. Meyer for helpful suggestions in the preparation of the paper and to Dr. R. S. Ostenso for the photography.

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PLATE XV

FIG. 4.

To illustrate article by Ann Marie Travis.

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FIG. 5.—Monkeys 50–10. An animal picking up raisins from a clipboard. Time values were compared with the speed of normal animals.

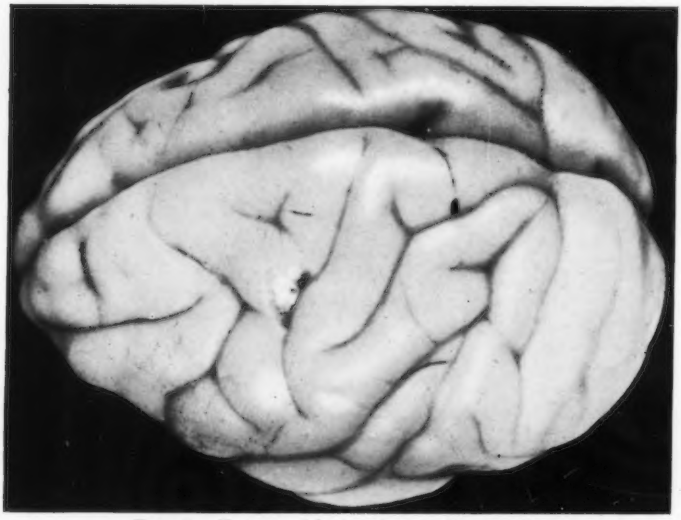

FIG. 6.—Extent of lesion in monkey 51–42.

To illustrate article by Ann Marie Travis.

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LEGEND

PLATE XV

FIG. 4.—Monkey **50-74** nine months following his second operation which completed the removal of the precentral limb areas bilaterally.

A. Maintains balance on bar of cage by grasping cage with only one hand. Grooming posture of right hand frequently observed. Note ability to completely extend the lower extremities and to grasp the wires of the cage with toes of feet.

B. Attempt to escape from cage. Hind-limbs are flexed while fore-limbs are nearly completely extended. Notice particularly the extension and slight fanning of the fingers.

C. Sitting on bar with lower limbs flexed in a similar to normal posture with no rotation of the thighs. Although the right hand was faster in performing than the left, he more frequently grasped the cage with the left hand.

D. Threatening observer. This illustrates his ease in balancing when standing upon bar of cage. The digits of all extremities are flexed. Flexion of the toes is significant in that animals with combined precentral and supplementary area lesions seldom flex the toes. He is able to flex or extend the elbows as evidenced by the posture of the upper extremities. No abnormal elevation of shoulders present.

E. Erect standing posture. Swaying of back probably due to his great weight and not significant of the lesion. Fingers of one hand are flexed while in the other they are extended.

F. A typical posture assumed in the examining chair. Observe the relaxed posture of upper limbs and flexed position of fingers as he holds on to the arms of the chair. Whereas a normal monkey keeps both feet constantly placed, this animal may place both simultaneously but more frequently just places one foot at a time. Toes of both feet are flexed.

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NEUROLOGICAL DEFICIENCIES FOLLOWING SUPPLEMENTARY MOTOR AREA LESIONS IN *MACACA MULATTA*[1]

BY

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THE "motor" cortex of the monkey has been redefined into *precentral* and *supplementary* motor fields (Woolsey and Settlage, 1950; Woolsey *et al.*, 1950, 1952) which do not correspond with the boundaries of the "motor" and "premotor" areas. This was the stimulus for the investigation of the effects of cortical removal according to these new maps (fig. 1). In this paper ablations involving the supplementary area will be described.

There is a divergence of opinion as to the ablation of which cortical area in monkeys is responsible for the phenomena of release. Kennard and Fulton (1933) attributed spasticity and forced grasping to ablations of the "premotor" area. Hines (1937) produced release phenomena by removal of a "strip" of cortical tissue in the anterior portion of the motor cortex. Denny-Brown and Botterell (1948) defined spasticity as a result of pyramidal (area 4) injury. Since no increased resistance to passive movements and no grasp reflex were present after ablation of the precentral motor area, although the removals included the dorsal upper part of the Vogts' area $6a\alpha$ and the dorsal portion of Hines' "strip" lesion (Travis, 1955) it was of interest to determine what release phenomena would result from removal of the supplementary motor field. It is believed that our data demonstrate that the supplementary motor area is partially concerned, at least, with inhibiting the phenomena of release in a somatotopic manner.

METHODS

Eight adult and four adolescent *Macaca mulatta* were studied. Operations were performed aseptically under anæsthesia produced by intraperitoneal injections of pentobarbital sodium, and the cortex was removed by subpial aspiration by Dr. C. N. Woolsey. The details

[1]This research was aided by grants from the Laukhoff Trust Fund, the National Institutes of Health, and the Wisconsin Alumni Research Foundation.

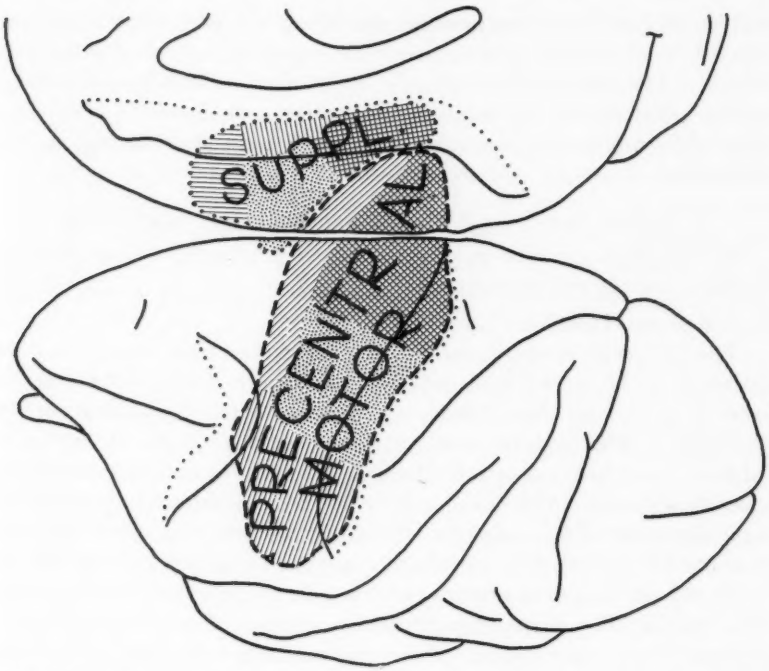

FIG. 1.—The extent of the precentral and supplementary areas of the monkey on the medial and dorsolateral aspects of the hemisphere. Each area is redivided into four smaller areas to represent localization of parts of the body: cross-hatching for hind-limb, dots for fore-limb, hatching most lateral in precentral motor and most anterior in supplementary area for face, and remaining two hatched areas for trunk musculature. The light dots parallel to the sulci for most of their distance designate the bottoms of the three sulci.

of surgical technique and examination procedures have been described elsewhere (Travis, 1955). The majority of the animals were maintained until maximal recovery occurred.

Photographs were taken of each brain after autopsy, and the accuracy of the lesions was determined by gross and histological data. Thalamocortical relations were studied (Akert and Woolsey, 1954); the brain-stem below the pons and, if the time interval was correct, also the entire spinal cord were used for Marchi degeneration studies (Barnard *et al.*, 1953).

RESULTS

A favourable arrangement of blood vessels, pipettes of correct size and shape, and careful surgical technique are required to remove the

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supplementary motor area without damaging the precentral hind-limb area. It is improbable that the *complete* supplementary area alone was ablated. The effects of removing the supplementary motor area include lesions restricted to the supplementary area and ablations involving either the supplementary or precentral motor areas with damage to the other area.

A. Lesions Involving Only the Supplementary Motor Area

The animals included in this section were believed to have lesions confined to the supplementary area.

(1) *Unilateral Ablations*

The *left supplementary motor area* was removed from monkey 50-130 (26.10.50; male; wt. 6·2 kg.) and observations were made for 6·5 months until re-operation. No paresis was present in the fore-limbs or left hind-limb. The hopping and placing reactions of the right lower extremity were heavy-footed on the first day and this extremity assumed a pendant posture in the examining chair for a month. The temporary right hind-limb deficit was probably due to minimal damage to the left precentral hind-limb area. On the first day the right pupil was 4 mm. as compared with a 2 mm. diameter on the left, but after five weeks pupils were equal. For three days hanging reflexes of 1–3 seconds were present in the right limbs. From the 21st to 130th day there was moderate resistance to protraction[1] and abduction of the arms, especially above shoulder level. After five months there was no resistance to protraction of the arms, although moderate resistance persisted to abduction. No hypertonia was present in the hind-limbs. Tendon reflexes were difficult to obtain.

The *left supplementary fore-limb area* was removed from monkey 51-69 (23.10.51; female; wt. 4·8 kg.) and autopsy was performed after five weeks. No paresis was observed. For two days hanging reflexes of 1–2 seconds were present in the right fore-limb. The shoulders were elevated and after a week moderate resistance existed to protraction and abduction of the arms.

Unilateral lesions of the supplementary area yielded no significant paresis. The resistance to passive movement was bilateral and suggests that the area has ipsilateral and contralateral representation. Why the hypertonia was localized at the shoulders is unknown. Data from additional preparations are needed to determine if this is a constant

[1]This terminology is that of Hartman and Straus (1933). Protraction and retraction are used instead of flexion and extension in order that identical terms may be used to designate the same directions of movement at the shoulder and hip.

finding. Weak, short-enduring grasp reflexes were obtained in the contralateral limbs.

(2) *Bilateral Ablations*

The *supplementary area* was moved *bilaterally* in monkey 50-149 (28.11.50; male; wt. 6·1 kg.) and observations were made for six months. For one week the animal was slower than normal. On the first day there was slight resistance to extension of the elbows and to protraction and abduction of the arms. After ten days resistance to abduction and protraction of the arms was observed to be stronger above shoulder level. Strong resistance to extension of the elbows was encountered, especially beyond the right angle position. There were flexion deformities of 30 degrees at the left elbow and of 20 degrees at the right elbow. After passive extension, the forearms resumed flexed postures. When the elbows were passively extended, either the wrists palmar-flexed and the lateral 4 fingers semi-flexed and fanned, or there occurred only semiflexion of the fingers (Plate XVII, fig. 2), which acted like springs after passive extension. After ten days there was moderate resistance to retraction of the thighs and to extension of the knees. After a month there were 45-degree flexion deformities of the knees. The hypertonia persisted. For a week tendon reflexes were difficult to elicit, but on the tenth day, and thereafter, triceps, finger, and toe jerks were hyperactive. Abdominal and plantar reflexes were not impaired. During the first week the right pupil was 3 mm. while the left was 3·5 mm. in diameter, but after ten days they were equal. No atrophy was present. For three days there were hanging reflexes in all extremities of 2–3 seconds, with duration of 5–14 seconds on the tenth day. The reflexes were absent after six weeks. On the second day placing and hopping were performed more slowly in the right limbs, but after a week no deficit was observed. After autopsy (24.5.51) the lesions seemed grossly limited to the supplementary area. Figs. 3A and B (Plate XVII) show the extent of the lesions.

The *supplementary area* was ablated *bilaterally* in monkey 52-1 (8.1.52; female; wt. 5·4 kg.). Except for elevation of the shoulders and constant flexion of the elbows, no deficit was found from observing general behaviour. Abdominal and plantar reflexes and hopping and placing reactions were not impaired. No atrophy occurred. On the third day there was moderate resistance to abduction and protraction of the arms, slight resistance to extension of the right elbow and to dorsiflexion of the ankles, and moderate resistance to retraction of the thighs. After three weeks tonus at the shoulders was unchanged. There was moderate resistance to extension of the elbows and dorsi-

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flexion of the left foot with slight resistance to dorsiflexion of the right foot. After five weeks there was moderate resistance to protraction and abduction of the arms. There was clasp-knife resistance to extension of the elbows, stronger on the right, and 20-degree flexion deformities. After passive extension, the forearms reassumed a flexed posture of 45 degrees. Moderate resistance was present to dorsiflexion of the wrists, but no hypertonus existed in the fingers. There was moderate resistance to retraction of the thighs and slight resistance upon external rotation of the thighs. Slight contractures of the hamstring muscles were present. Strong resistance existed to dorsiflexion of the feet beyond the right angle position. Triceps and knee jerks were difficult to obtain. The biceps, finger, Achilles, and toe jerks were hyperactive. On the first day grasp reflexes of 10–15 seconds were present in all limbs but were absent after six weeks.

The two preceding preparations with *bilateral supplementary area ablations* confirm and supplement each other. Paresis was slight, and the greatest disturbances were observed in posture and tonus. The increased resistance to passive movements and contractures were encountered in the flexor muscles of upper and lower extremities, and the majority of joints were involved in each animal. Since dorsiflexion of the foot is anatomical extension, it is therefore not surprising that hypertonia was observed in the flexors of the ankle. The results suggest that if the complete supplementary motor area were destroyed bilaterally all joints would be involved. They also support somatotopic localization within the area. Certain tendon reflexes were hyperactive, and the grasp reflexes following bilateral removal persisted four to six weeks. *The greater deficits obtained after bilateral as compared with unilateral ablations demonstrate that the supplementary area is a bilateral functioning system.*

B. Ablations Involving the Supplementary Motor Area with Injury to Precentral Motor Area

In monkey 50–79 the *supplementary area* was ablated *bilaterally* with *damage to the left precentral hind-limb area* (5.7.50; male; wt. 6·8 kg.; re-operated after 4·5 months). Slight paresis was observed in the hands for one week. For two weeks the animal for the most part sat on the floor of the cage. After two weeks the right hind-limb was placed secondarily to the left in climbing to and from the perch and frequently caught upon the bar. This impairment persisted during the eleven months' survival period. The shoulders were elevated and strongly adducted, and the elbows usually flexed at right angles. On the second day there existed moderate resistance to protraction and

abduction of the arms, slight resistance to extension of the right elbow, and strong resistance to extension of the left elbow, to retraction of the left thigh and to extension of the left knee. On the sixth day moderate resistance to extension of the left elbow beyond a right angle position was present. The lateral 4 fingers of both hands were flexed at the first interphalangeal joints and returned like springs after passive extension. Strong resistance was present to retraction of the left thigh with slight resistance to retraction of the right. There was resistance to extension of the knees, greater on the left. On the twelfth day moderate resistance was encountered to extension of the elbows, and 30-degree flexion deformities were present. After a month there was strong resistance to abduction and protraction of the arms with 45-degree contractures. The right knee had a flexion deformity of 20 degrees and the left knee 30 degrees. With passive extension of the knees, there occurred inversion of the feet and 8–12 clonic contractions of the hamstring muscles. After ten weeks maximal hypertonia was present, which persisted. There was strong resistance to protraction and abduction of the arms with vigorous clonic contractions of the latissimus dorsi muscles and inability to raise the arms above shoulder level. Strong resistance with clonic contractions in the biceps muscles was encountered to extension of the elbows beyond the right angle position; flexion deformities of 45 degrees were present. With passive extension of the elbows, the wrists were frequently palmar-flexed; the thumb adducted and flexed; the fingers either flexed at the metacarpo-phalangeal joints and fanned, or adducted and semiflexed at all joints to produce "cupping" of the palms. At the thighs there was moderate to strong resistance to retraction, greater on the left, with no resistance upon rotation. Flexion deformities of 45 degrees on the left and 30 degrees on the right existed at the knees. No abnormal resistance was present at the ankles or toes. The contractures persisted under anæsthesia. On the first day, and thereafter, triceps, biceps and finger jerks were hyperactive. For two weeks the right knee and toe jerks were hyperactive. After this interval the knee, crossed adductor, Achilles, and toe jerks were hyperactive bilaterally. There was no impairment of abdominal reflexes. Normal plantar reflexes were obtained on the left; on the right there were twitching and apposition of the hallux and second toe. Pupils were equal. After two weeks maximal atrophy of 5 per cent was present in the right hind-limb only, which was absent after six weeks. On the first day grasp reflexes lasting 10 seconds were present in the fore-limbs when tested individually and lasting 25 seconds when tested simultaneously. Hanging reflexes of

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8–10 seconds were present in the left or right limbs when tested simultaneously. After a month these reflexes could not be elicited. No deficit in placing or hopping was detected in the left limbs. After two weeks the placing reactions returned in the right fore-limb and after a month the animal hopped slowly with this extremity. After five weeks placing and hopping reactions were excellent in both upper limbs. After a month he slowly placed the right hind-limb, and after seven weeks slow hopping occurred upon forward and lateral displacements. These reactions continued to be slowly performed in the right lower limb.

Figs. 4A, B and C (Plate XVIII) show the extent of the lesions in monkey 50–79 and confirm that there was damage to the left precentral hind-limb area. The left supplementary hind-limb area appeared more completely removed than on the right. Greater hypertonia and contractures were present in the left lower extremity, which was opposite the supplementary lesion alone. The temporary deficit of the placing and hopping reactions in the right fore-limb was probably due to cortical œdema from the larger lesion in the left hemisphere. After this temporary paresis, the hypertonia and contractures in the upper extremity were equal. Since from gross inspection the supplementary representations for the distal hind-limbs were not removed, this could explain why no hypertonia was found at the ankles or toes. The hyperactive tendon reflexes were prominent. Transient grasp reflexes, lasting three weeks, were observed.

The following experiment is included to demonstrate an interesting finding concerning bilateral removal of the supplementary area in *two* stages. In monkey 50-130 *the right supplementary area and the right precentral hind-limb representations* were removed at a second operation after ablation of the left supplementary area 6·5 months previously (*see* heading A; 9.5.51; wt. 7·15 kg.). No impairment was detected in the right limbs. For three days there were slight paresis and hypertonia in the left fore-limb. For a week the left hind-limb displayed marked paresis and hypertonia. After three weeks this limb assumed a flexed posture, except that the toes were extended. The tonus in the lower extremities was approximately equal after two months. There was no hypertonia except to dorsiflexion of the ankles, moderate on the left and slight on the right, and this hypertonia persisted. The resistance at the shoulders that occurred after the first operation disappeared four months after the second operation. On the first day, and thereafter, the left knee-jerk was hyperactive. Other tendon reflexes were difficult to obtain. Abdominal reflexes were diminished on the left for a month. Plantar reflexes were absent on the left for two weeks, and after maximal

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recovery there occurred only twitches in the hallux and second toe. The left pupil was 2·5 mm. and the right 2 mm. in diameter for four days, after which they were equal. On the first day there were grasp reflexes of 5 seconds in the right limbs and the left fore-limb but these disappeared after a week, persisting longest in the left fore-limb. Placing and hopping reactions were unimpaired in the right extremities. The hopping and placing reactions were absent in the left hind-limb and deficient in the left fore-limb for two weeks. After three weeks he hopped slowly forward and laterally with the left lower extremity, whose reactions remained impaired. There was exaggerated flexion of the limb; it was thrust far forward, and the monkey landed on his toes.

This preparation demonstrates that *if the supplementary area is removed bilaterally in two stages, no significant spasticity will be observed following the second operation provided sufficient time intervenes between operations.* This animal demonstrates that *the supplementary area also controls voluntary movements,* for greater paresis was observed in the left hind-limb than is obtained after removal of the precentral hind-limb area alone. The grasp reflexes were weaker and of shorter duration than following simultaneous bilateral supplementary area lesions. The longer persistence of the grasp reflex in the left fore-limb demonstrated that it was stronger in the limb contralateral to the second supplementary ablation. Crude hopping and placing was elicited in the left hind-limb. We have found that if the precentral and supplementary hind-limb areas are removed *unilaterally,* these reactions are not obtained; but previous, simultaneous, or subsequent removal of either or both hind-limb areas in the opposite hemisphere permit the reactions to be performed.

C. Lesions Involving the Precentral Motor Area with Injury to the Supplementary Motor Area

In monkey 50-19 *the precentral motor area and the supplementary area as far rostral as the anterior boundary of the precentral motor cortex* was removed *on the left; on the right "area 6" rostral to the precentral motor cortex* was ablated which extended on the medial wall to the sulcus cinguli and involved all the supplementary face and possibly distal representations of the supplementary fore-limb area (22.2.50; male; wt. 7·7 kg.; autopsy after seven weeks). On the second day he climbed upon his bar. There was no deficit of the left limbs, but the right limbs were in gross malpositions. The right face drooped, and food remained in the right pouch. On the third day he elevated the right shoulder once to empty the right pouch. The right hand

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aided the left in picking pieces of banana from the left toes. He elevated the right hand nearly to the mouth and licked the banana from the right fingers. After three weeks the right fore-limb assumed a spastic posture with shoulder elevated and adducted, elbow flexed at a right angle, wrist palmar flexed, and lateral four fingers flexed at the first interphalangeal joints. The right limbs participated in co-ordinated, associated movements (climbing and walking). After a month, if forced to under unusual circumstances, the right hand accepted and transferred food to the mouth, but fingers were used as a claw. Right fingers and toes seldom grasped. In climbing from the perch, the right foot frequently caught upon the bar. When one hit the side of the cage while he was sitting on the bar, the right limbs were immediately raised from their resting positions and held for 2 to 5 minutes in flexed postures before gradually relaxing. The left extremities were undisturbed by the sudden jarring and noise. For two days the right fore-limb was hypotonic. On the third day and thereafter hypertonia of this extremity existed, but no contractures developed. Slight resistance was encountered to protraction and abduction of the right arm, and moderate resistance was offered to extension of the right elbow beyond a right angle position. The right fingers returned to semi-flexed postures after passive extension. Only slight hypertonia existed in the right hind-limb. The tendon reflexes on the right were impaired for a week but after this were hyperactive. For three weeks the right abdominal reflexes were hypoactive but after four weeks were as active as on the left. Upon pricking the heel and medial surface of the right foot with a pin, apposition of the hallux and second toe occurred. For three days, when measured in subdued light, the right pupil was 5 mm. while the left was 4 mm. in diameter. A maximal atrophy of 12·3 per cent over the biceps muscle and 14·5 per cent over the calf muscles was present in the right limbs after three weeks, and 10 per cent atrophy in the right extremities existed after seven weeks. Hanging reflexes were present in the left limbs for two days, stronger in the hand (5–10 seconds) than the foot (3 seconds). Placing and hopping reactions were absent in the right limbs. Autopsy (10.4.50) was performed because of a positive tuberculin skin test. Fig. 5 shows the extent of the lesions.

This preparation again defines the supplementary motor area as concerned with controlling movements, a function not evident after removal of the supplementary area alone. *The paralysis after unilateral ablation of the precentral and supplementary areas was much greater than observed after lesions of the unilateral precentral motor area alone.* The placing and hopping reactions were persistently absent in the right

limbs. The resulting hypertonia and hyperactive reflexes demonstrate that release phenomena occur in the contralateral limbs after combined unilateral precentral and supplementary motor area removals. The inability to obtain grasp reflexes in the right limbs would support the clinical findings, at least after unilateral lesions, that forced grasping may cease when the "motor" area becomes extensively involved.

In monkey 50-98 the *precentral and supplementary fore-limb areas on the right and the left precentral fore-limb area* were ablated (23.8.50; wt. 2·6 kg.). On the first day there was marked paresis of the upper limbs. After a month fine finger movements were observed in the right hand. When each hand was tested to determine its speed in picking up raisins, the right hand averaged 0·8 second and the left 1·5 seconds per raisin. After a week the left fore-limb assumed a spastic posture with shoulder elevated and adducted, elbow flexed 45 degrees, and fingers semiflexed. This posture was maintained for a month, after which the posture was similar to that on the right. There was slight hypertonia of the left fore-limb, especially to extension of the left elbow. After three weeks he placed and hopped slowly with both fore-limbs, but the left was persistently slower than the right. He placed the right upper extremity to cotton stimulation and hopped in all directions. The left upper limb hopped only forward and laterally and did not place to cotton stimulation. After eighteen months the left hand was more deficient than the right.

The greater paresis in the left fore-limb of the preceding animal demonstrates that *the supplementary area exerts some control over movements of the contralateral extremities*. The additional precentral area lesion in the opposite hemisphere allowed the affected fore-limb contralateral to the unilateral precentral and supplementary lesion to perform crude hopping and placing.

Monkey 5-70 had previous bilateral ablation of the precentral fore-limb area which has been described elsewhere (Travis, 1955). At a second operation *the precentral hind-limb area* was removed *bilaterally with damage to the supplementary limb areas* (25.10.50; male; wt. 9·0 kg.; autopsy after seven months). No additional deficit was observed in the left fore-limb, but the right fore-limb was used reluctantly for three days. For two weeks he seldom climbed on the bar but sat on the cage floor. Occasionally both hind-limbs were extended, but more frequently the thighs were externally rotated, knees partially flexed, feet inverted, and toes extended. After a month he sat on the bar part of the time, and the feet placed against the cage with toes extended. After seven months he preferred sitting on the cage floor and remained clumsy on

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his feet. He grasped the monkey chair with both hands but hind-limbs remained pendant with toes extended and usually fanned; halluces abducted, and feet plantar-flexed. On the second day and thereafter strong resistance was present to dorsiflexion of the feet, greater on the right. After a month there was slight resistance to extension of the elbows with flexor contractures of 20 degrees. Fingers were usually flexed and after passive extension returned like springs to flexed postures. After two months flexor contractures of 30 degrees were present at the knees. Slight resistance was present to external rotation of the thighs with moderate resistance to retraction. Contractures at the knees and elbows persisted for seven months. On the first day and thereafter triceps, biceps and finger jerks were hyperactive. The knee-jerks were brisk with small excursions. The Achilles and toe jerks were difficult to obtain. For two weeks there were weak abdominal reflexes, but after twenty-five days the reflexes were active and equal on both sides. Slight twitches in the hallux and second toe occurred upon stroking the sole of either foot. Pupils were equal. Atrophy in the fore-limbs reached a maximum of 13·4 per cent after two weeks and disappeared after a month. In the hind-limbs the greatest atrophy was observed after a month, which was 15·7 per cent, and disappeared after two months. For two months there were hanging reflexes of 10–12 seconds when right or left extremities were tested simultaneously and of 15–20 seconds when the fore-limbs were tested simultaneously. After seven months hanging reflexes of 3–5 seconds were present in the limbs. Placing and hopping reactions were slowly performed in the fore-limbs, slower on the right, and fingers fanned moderately. After a month the lower extremities hopped slowly laterally and forward, and toes fanned as he performed the reactions. Only a suggestion of placing was obtained in either hind-limb and hopping remained poor. Autopsy (5.6.51) was performed, and figs. 6A and B (Plate XIX) are photographs of the brain.

This preparation demonstrates that *the supplementary area influences movement and the inhibition of phenomena which are released by its destruction*. Paresis is much greater when the supplementary area is encroached upon in removing the precentral motor area. Grasp reflexes occurred in all limbs.

In monkey 50-135 *Hines' "strip" area exclusive of medial wall portion was removed bilaterally* (2.11.50; female; wt. 5·5 kg.; autopsy after six months and three weeks). No paresis was observed. On the first day shoulder and hip muscles were hypotonic as compared with the distal musculature. On the second day the shoulders were elevated

and adducted and there was moderate to strong resistance to abduction and protraction, stronger on the right; this hypertonia persisted. Under anæsthesia 45 degree contractures existed at the shoulders. No increased resistance was present at the hips or other parts of the limbs. Tendon, abdominal and plantar reflexes were normal. Pupils were equal, and there was no atrophy. Grasp reflexes were absent. Deficiencies of placing and hopping were observable for a week. Contact placing was slow when the anterior surface of the extremities was touched. The hind-limbs hopped well medially, laterally, and backward, but slowly forward, requiring a larger displacement than normal to initiate movement. In the fore-limbs hopping was slowly executed forward and laterally. There was better use of distal than proximal joints. An autopsy (26.5.51) was performed without perfusion 4 to 6 hours after completion of a dorsal root dermatome experiment. Fig. 7 is a photograph of the brain after fixation.

The paresis of the shoulders and hips in this animal fits the precentral motor pattern. Although not apparent grossly, it is believed that there was interruption of some of the fibres from at least one supplementary motor area. Hypertonia at both shoulders occurred in the two animals with unilateral supplementary area lesions. In monkey 51-44, reported previously (Travis, 1955) the "strip" area rostral to the precentral hand-finger area was removed bilaterally, and no hypertonia resulted.

In monkey 51-29 the *left precentral motor area* was removed (18.5.51; male; wt. 3·2 kg.; autopsy after one month). On the first day he grasped the cage with the right toes and fingers and flexed the knee and elbow on the right. After ten days he took food slowly with fine finger movements of the right hand. Right limbs placed secondarily to the left extremities. On the first day the right limbs were hypotonic, except for slight increased tonus at the right elbow. After a month the tonus in the right limbs was equal to that observed on the left. No contractures resulted. For two weeks tendon reflexes were more difficult to elicit on the right, but after a month triceps, finger, knee and toe jerks were more active on the right. Abdominal and plantar reflexes were persistently impaired on the right. For two weeks grasp reflexes were present in the right limbs when tested simultaneously—fore-limb (5 seconds) and hind-limb (2–3 seconds). Placing reactions were slowly performed in the right limbs. Hopping reactions were initiated in the right limbs after maximal displacement, were present in all directions, but were best upon forward or lateral displacement. At autopsy (18.6.51) grossly the lesion appeared as intended (fig. 8).

The moderate hypertonia present at the right elbow of the preceding

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preparation was probably due to damage to the supplementary fore-limb area. Removal of precentral fore-limb area alone, with no damage to the supplementary area, yields no hypertonia (Travis, 1955). The grasp reflexes also suggest damage to the supplementary area, as lesions confined to the precentral motor area give no grasp reflex.

D. Ablation of Dorsal and Lateral "Area 6" Not Included in the Precentral Motor Area

Two experiments were performed to determine if the portion of the supplementary area located on the medial wall in "area 6" plus the trunk musculature representations of the precentral motor area might not be the only motor functional part of the "premotor" area.

Monkey 50-10 had bilateral precentral limb areas ablated in four previous operations. At a fifth operation (24.11.50; wt. 8·8 kg.) *bilateral dorsal "area 6" rostral to the precentral motor area* (Vogts' area 6a β) *plus the right orbitofrontal cortex* was removed. There was no additional impairment or hypertonia of the extremities. The tendon reflexes and tonus were unchanged. No grasp reflex resulted.

From monkey 50-79 (with a former bilateral supplementary ablation described under heading B) *bilateral dorsal "area 6" rostral to the precentral motor area* was removed at a second operation (22.11.50; wt. 7·4 kg.) His motor status was unchanged. Tendon reflexes continued hyperactive, and the hypertonia persisted unaltered. No grasp reflex was observed. At a third operation (21.3.51; wt. 8·0 kg.) *bilateral "area 6" lateral to the precentral face area* was ablated. No change in the motor status of the limbs resulted. For a week he chewed slowly and food remained in the pouches for long periods of time, probably due to damage of the precentral face areas. No grasp reflex was present. At autopsy (2.6.51) photographs of the brain were taken, and the gross lesions are shown in figs. 4A and B.

These preparations demonstrate that *lesions of dorsal and lateral "area 6" not included in the precentral motor area do not contribute observable motor deficit of the limbs. The only motor functional portions of "area 6" are those included in either the precentral or supplementary motor areas.*

Discussion

These ablational studies have defined the supplementary motor area as a functional entity concerned with posture, movement, and the inhibition of release phenomena. An attempt will be made to relate these results to previous ablational data involving the histologically mapped "motor" (area 4) and "premotor" (area 6) areas. Former lesions continued to

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the bottom of the sulcus cinguli and included the cortex on its dorsal surface. Therefore, the extent of the supplementary area removed with area 4 or 6 lesions depended on the rostral boundary of area 4. If the Vogts' cytoarchitectural map (1919) was used, the extirpation of area 4 included the supplementary hind-limb area. If ablations were made by Brodmann's (1909) original map, the removal of area 4 destroyed the supplementary hind-limb area and possibly most, if not all, of the supplementary fore-limb area. The supplementary fore-limb and face areas, along with the proximal limb centres of the precentral motor area, were included in lesions of the Vogts' area 6 or the "premotor" area of Fulton. Brodmann's area 6 included all of the supplementary face area and perhaps a small portion of the supplementary fore-limb area.

This study demonstrates that the supplementary area is a bilateral system, for unilateral lesions produced minor deficits; whereas, simultaneous bilateral removals yielded more prominent effects on posture and tonus. Stimulation of the supplementary area has yielded only contralateral responses, which might be attributed to the stage of anæsthesia under which the stimulations were made. Bucy and Fulton (Bucy, 1933; Bucy and Fulton, 1933) reported ipsilateral (i.e. bilateral) representation in the monkey's "motor" and "premotor" areas. They found that bilateral removal of areas 4 and 6 produced a helpless animal; whereas, if either the "motor" or "premotor" area was left intact in one hemisphere, the monkey was capable of volitional movements. Since we have produced adult monkeys that can sit, walk, climb, and feed themselves after bilateral removal of areas 4 and 6 (Travis and Woolsey, 1952) some uncertainty is raised as to whether the ablational evidence of Bucy and Fulton establishes the existence of ipsilateral motor representation. Fulton and Kennard (1934) concluded that in monkeys, baboons and chimpanzees bilateral representation was present in the "motor" and "premotor" areas, but especially in the latter. Fulton (1932) found bilateral representation in the motor foot area of the chimpanzee. Foerster (1931) found an indication of bilateral representation in the motor foot area of man. The results obtained by these workers can probably be explained by involvement of the supplementary area in conjunction with the precentral area removals. Furthermore, Fulton and Kennard (1934, p. 204) stated, "Evidence of bilateral representation of the upper extremity is unsatisfactory." Since extirpation of the precentral fore-limb area yielded no indication of bilateral representation (Travis, 1955), our findings in this respect support their statement. Our results, in addition, give no evidence for ipsilateral representation in the precentral hind-limb area.

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Unilateral supplementary area lesions produced no noticeable paresis, but within a week moderate bilateral hypertonia was present at the shoulders and persisted six months, although diminished in quality. Why the hypertonia was limited to the shoulder is unknown. Further experiments will be necessary to determine if this is a constant phenomenon with unilateral lesions. Our findings agree closely with those of Penfield and Welch (1949, 1951) who found that unilateral excision of supplementary area in man yielded no permanent impairment of posture or movement.

Simultaneous bilateral ablation of the supplementary area yielded little paresis, but posture and tonus were greatly disturbed. Immediately there was increased resistance to passive movements in the flexor muscles, and during an interval of two to four weeks contractures supervened. The tendon reflexes were hyperactive with finger and toe jerks demonstrating clonus. Hines (1937) by removal of the "strip" area in monkeys first experimentally isolated spasticity from its companion, paralysis. Our results correlate closely with the data of Hines (1937, p. 322) who stated, "Furthermore, if one medial surface of this strip of cortical tissue be preserved, the phenomena of release will be transient. Subsequent removal of this one medial surface reproduced all of the phenomena in all four extremities, stronger on the ipsilateral side." We found after bilateral ablation of the portion of the "strip" area restricted to the precentral motor area that no spasticity resulted, but as the "strip" lesion encroached upon the supplementary area release phenomena followed. This investigation demonstrates that the supplementary motor area is the functionally important portion of Hines' "strip" lesion.

We have not sufficiently investigated the efferent pathways leaving the supplementary motor area and do not know to what extent it is served by pyramidal and extrapyramidal systems. Since Tower (1940) produced a hypotonic paresis with no spasticity by medullary section of the pyramidal tract, it is assumed that the fibres arising from the supplementary area whose interruption yields the phenomena of release belong to the extrapyramidal pathways.

Simultaneous bilateral removal of the supplementary areas yielded spasticity unaccompanied by significant paralysis. Spasticity and paralysis do appear separately in man. Spielmeyer (1906), Hoestermann (1912), and Finkelnburg (1913) reported cases in which spasticity was present even though the pyramidal tract was anatomically intact. Bergmark (1909) reported a few cases of monoplegia of cortical origin with no accompanying spasticity. Tower (1940) proved, as Walshe

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(1919) originally predicted, that the typical spastic hemiplegic reveals a component other than the cortico-spinal system.

The hypertonia and hyperactive reflexes after simultaneous bilateral supplementary removals suggested topographical localization according to the portion of the area removed. Hines (1937) reported that the phenomena of release resulting from injury of the "strip" area showed no evidence of topographical localization. Fulton (1949) concluded that spasticity was a function of no one area but of the extent of involvement of the extrapyramidal cortical pathways. *The first cortical area to suggest topographical localization in the production of spasticity* following ablations *is the supplementary motor area.*

When the supplementary area was removed bilaterally in two stages with over six months intervening between operations, only slight increased resistance, located at the ankles, followed the second operation. This indicated that recovery intervened between operations, but the minimal time necessary for this to occur has not been determined and the mechanism is unknown.

In clinical cases spasticity and paralysis are frequently combined, and much experimental work is concerned with lesions producing both phenomena. Although unilateral supplementary lesions produced only slight bilateral phenomena of release, unilateral removal involving the supplementary and precentral motor areas yielded spasticity of the contralateral extremities. It has long been a controversial question whether lesions restricted to area 4 produce spasticity. In an attempt to solve this problem Denny-Brown and Botterell (1948) performed many experiments in monkeys limited to area 4. Most of their lesions, although involving the caudal portions of area 4, usually damaged the supplementary as well as the precentral motor area. Their incisions extended to the cingulate sulcus, and a block of tissue was removed by blunt dissection or by peeling off the grey matter. These workers found spasticity greater even when the lesions were limited to the caudal part of area 4, but the hind-limb usually showed the greatest spasticity. Since the supplementary hind-limb area lies on the dorsal bank of the cingulate sulcus as far caudal as the central sulcus, interruption of these fibres with removal of caudal area 4 probably was responsible for the spasticity obtained.

How do our results in *Macaca mulatta* correlate with findings concerning unilateral spastic paralysis in man? Foerster (1936*a*, 1936*b*) found that motor disturbances and spasticity resulting from excision of the leg area, strictly limited to area 4, did not differ from that due to destruction of the entire leg area (both areas 4 and 6$a\alpha$). If the supple-

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mentary hind-limb area in man is located in an analogous position to that in the monkey, with removal of the Vogts' area 4 the representation for supplementary and precentral hind-limb is destroyed. According to our maps area $6a\alpha$ of the Vogts involves mainly the trunk musculature of the precentral motor area. Since spasticity was isolated in the contralateral limbs, only by the combined involvement of the precentral and supplementary areas would one expect to find maximal spasticity. Clinically, it is often assumed that since spasticity results from removal of area 4 hind-limb representation, that spasticity would occur if the area 4 fore-limb was ablated. Foerster had no cases limited to the arm and finger areas of the motor system. Bucy (1949) described a patient having a motor arm area lesion alone who had no increased resistance to passive movement. In another case, after removal of the arm and leg areas which included ablation of area 6, Bucy found a greater deficit and spasticity occurring in the upper extremity after the combined lesion of arm and leg areas than after removal of arm area alone. This was most likely due to additional damage to the supplementary fore-limb area. Foerster (1931) mentioned a patient who had spastic paralysis limited to one foot as a result of syphilis affecting one precentral gyrus. Walshe (1935) reported a case in which the foot and toe representation of area 4 on the medial aspect of the hemisphere were removed. Permanent impairment of movement with considerable spasticity at the contralateral ankle resulted. Walshe concluded that the premotor syndrome was predominantly a syndrome of the true motor cortex, and that the hypertonus existed usually in the most paralysed part of the limb. Our ablational as well as stimulation experiments, however, support the idea of two functional motor areas. The localization of the precentral and supplementary hind-limb areas adjacent to one another has probably led to many of the diverging conclusions in the literature.

What experimental data have we obtained concerning spastic paralysis after bilateral lesions? Contractures were lessened and delayed by the involvement of the precentral motor area in addition to the supplementary area. The animals with complete bilateral removal of the precentral and supplementary limb areas have been reported (Travis and Woolsey, 1952) and will be discussed in detail later. Walshe 1914–15, p. 326) stated that "In a cerebral lesion or in a purely pyramidal tract affection, however complete, we see constantly the extended type of paralysis in the leg." He found that spastic paralysis with flexor contractures resulted in the lower limbs only after spinal cord lesions and never after mere involvement of the pyramidal tract. Our results indicate that it is possible to produce spastic paralysis in the hind-limb of the

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flexor type from a cortical lesion, but we would attribute this spasticity to the interruption of cortical extrapyramidal pathways. Marie and Foix (1920) reported a case of paraplegia in flexion of long standing produced by a lesion of both paracentral lobules. Alajouanine (1923) reported additional clinical cases to support the finding of Marie and Foix and produced paraplegia in flexion in the dog by ablation of both paracentral gyri. Welch and Kennard (1944, p. 263) after bilateral ablation of the medial part of "area 6" in one monkey found that "ablations here more greatly influence flexor posture than paresis." These authors very probably damaged the precentral hind-limb area as well as the supplementary limb areas for the hind-limbs were more severely paralysed than the fore-limbs.

Foerster (1931) reported a few cases which could be interpreted as localized bilateral involvement of the supplementary and precentral areas. In one patient bilateral spastic paralysis of both feet resulted from a gun-shot wound affecting the medial portion of each "motor" area. Movements of the legs and thighs were undisturbed. One case with a meningioma of the falx cerebri had spastic paralysis of both legs. These results demonstrate the localization of lesions giving rise to spastic paralysis.

Either unilateral or bilateral ablations restricted to the supplementary motor area produced no significant disturbance in movement. The proof that the supplementary area has some control over movements was derived from another type of experiment. Either unilateral or bilateral combined lesions of the precentral and supplementary motor areas caused greater paralysis than ablations restricted to the precentral motor area. Jacobsen (1934) after removal of the Vogts' area 6 found a permanent deficit in the animal's capacity to make skilled motor adjustments. Kennard, Viets, and Fulton (1934) found a similar disturbance of skilled movements in man. The greater deficit that these authors obtained upon removal of "area 6" was probably due to the simultaneous partial interruption of the precentral motor area along with damage to the supplementary area. This would occur upon removal of the Vogts' upper $6a\alpha$. Hamuy (1951) studied the retention of skilled movements in several of our animals after a constant neurological status was reached post-operatively. After bilateral supplementary motor lesions the animals were handicapped on the crank box because of spasticity in the fore-limbs, but showed no deficit in the ability to pick up small moving objects or to operate simple and complex problem boxes (Hamuy, 1951).

A temporary grasp reflex was produced by unilateral and bilateral

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removals restricted to the supplementary area, being of longer duration after bilateral lesions. Adie and Critchley (1927, p. 161) concerning forced grasping in man after unilateral lesions stated, "we are inclined to think that the lesion responsible for these symptoms is in the upper and posterior part of the frontal lobes. This is suggested by the site of the lesion in a number of cases, and is perhaps supported by the fact that in a great many cases the leg was definitely weaker than the arm." With removal of the supplementary area little motor impairment of the fore-limb results, but paresis in the lower limb could occur with damage to the adjacent precentral hind-limb area. Adie and Critchley reported that forced grasping disappeared as paralysis became complete, and we found similar results upon unilateral simultaneous removal of the precentral and supplementary motor areas in two animals. In one animal we found temporary grasp reflexes after unilateral removal of the precentral motor area with slight damage to the supplementary area. If one tested the animals frequently enough a temporary grasp might appear after the period of greatest paralysis, as was observed by Fulton (1934) in the chimpanzee.

Ritcher and Hines (1932) further localized the lesions responsible for the grasp reflex by frontal lobe lesions in monkeys. *Unilateral* removal of "area 6," including the *medial* surface of the hemisphere as far ventral as the corpus callosum, produced a transient hanging reflex in the contralateral hand. Fulton, Jacobsen, and Kennard (1932) confirmed these findings and extended observations to another species of monkey and to baboons. Penfield and Welch (1951) recently showed that the grasp reflex was a sign of injury to the supplementary motor area in unilateral lesions in the monkey. Erickson and Woolsey (1951) reported a weak and short-enduring grasp reflex after *unilateral* involvement of the supplementary area in man. We have confirmed these results and have obtained a weak, temporary hanging reflex in the contralateral limbs after removal of the supplementary area. Little, if any, stronger grasp was obtained upon additional removal of the prefrontal cortex including the Vogts' area *6aβ*.

Bilateral removal of "area 6" plus the gyrus cinguli just ventral to this cortical area was reported by Ritcher and Hines (1934) to produce permanent involuntary grasping. The lack of permanency we obtained after bilateral supplementary lesions might be due to the non-involvement of the gyrus cinguli just ventral to the supplementary area. Kennard and Fulton (1933) found a transient grasp after bilateral removal of "area 6" in chimpanzees, which persisted longer after bilateral than after unilateral ablations. Welch and Kennard (1944)

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found temporary grasp reflexes after bilateral ablation of medial "area 6" in one monkey. Erickson and Woolsey (1951) reported transient grasp reflexes that ocurred in 2 patients after *bilateral* involvement of the supplementary area. Our observations further emphasize that lesions of only the supplementary motor area produce grasping phenomena.

In our experiments no motor impairment, spasticity, or grasp reflexes were found after removal of the portion of "area 6" not included in the precentral and supplementary motor areas. These findings agree with those reported by Foerster (1936, p. 156) after excision of area 6aβ in man, who reported that in "no case were forced grasping or the slightest degree of spasticity observed." Hines (1937) found that ablation of area 6 by Brodmann's original map produced no paralysis or spasticity, but a grasp reflex was observed in the hand. The results obtained were probably due to involvement of the supplementary finger area. In our experience stimulation of dorsal "area 6" not included in the precentral motor area produces only dilatation of the pupils, and this area is possibly part of a cortical autonomic system. Frequently with removal of the supplementary area or upon ablation of the precentral limb areas, we obtained temporary pupillary inequality. Since these areas lie adjacent to the Vogts' dorsal part of area 6aβ, injury or cortical œdema could involve this pupillary field. Since at times the contralateral pupil was larger while at other times smaller than the pupil on the same side as the operation, there are possibly representations for dilatation and constriction in this pupillary field.

The atrophy that we obtained seemed to support the theory of disuse. There was no observable paralysis after lesions of the supplementary area and no atrophy existed. Upon removal of the precentral and supplementary motor areas, there resulted greater paresis and muscle wasting than after ablation of the precentral area alone. The atrophy lessened as voluntary movement returned.

Although no deficit in the placing and hopping reactions was detected after unilateral and bilateral lesions of the supplementary area, interesting findings were observed after combined lesions of the precentral and supplementary motor areas. After unilateral ablation of the precentral and supplementary motor areas, hopping and placing could not be evoked in the contralateral limbs. After removal of Brodmann's area 4 Woolsey and Bard (1936, unpublished) found similar results for survival periods as long as two years. If in addition the intact cerebral hemisphere be subjected to an ablation of either the precentral or supplementary motor area, poor hopping and placing reactions were obtained in the limb which was unable to hop or be placed after combined uni-

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lateral lesions alone. Woolsey and Bard (unpublished) noted the same phenomenon after removal of Brodmann's area 4 in the opposite hemisphere which we have observed after bilateral removal of the entire precentral and supplementary motor areas (Travis and Woolsey, 1952). The question why a limb opposite to a unilateral precentral and supplementary motor lesion is unable to accomplish these reactions until one or the other or both of the areas are removed in the opposite hemisphere cannot be answered satisfactorily. It is possible that the precentral and supplementary motor areas acting together produce an inhibitory influence upon the subcortical mechanism controlling the ipsilateral limb. Lower animals are able to perform the hopping and placing reactions after unilateral removal of the motor cortex or the entire hemisphere. In the monkey we are dealing with an original subcortical mechanism upon which the cortex has not only added independence of function but also probably "inhibition."

The most important contribution of this study was the defining of the supplementary motor area as a functional entity concerned with the control of posture, movement, and the inhibition of release phenomena. The removal of the supplementary motor area seems to produce topographical localization of spasticity. It appears that the precentral and supplementary motor areas for the most part exert different influences on the motor reflex systems described by Sherrington (1947, p. 302), "Two separable systems of motor innervation appear thus controlling two sets of musculature : one system exhibits those transient phases of heightened reactions which constitute reflex movement; the other maintains a steady tonic response which supplies the muscular tension necessary to *attitude* . . . These two systems, the tonic and phasic reflex systems, co-operate, exerting influences complemental to each other upon various units of the musculature."

Summary

The supplementary motor area was defined by electrical stimulation as a distinct somatotopically organized field (Woolsey *et al.*, 1950, 1952), and this investigation was undertaken to determine the neurological deficits produced by its removal. The results were derived from lesions restricted to the supplementary area and from ablations involving either the precentral or supplementary motor area with injury to the other area. Experiments were also performed to determine if extirpation of the portions of the histologically mapped "area 6" not included in the precentral motor area would demonstrate motor impairment. The results are as follows :

(1) The supplementary motor area is a *bilateral* functioning system, for greater deficits were obtained after simultaneous bilateral than after unilateral ablations.

(2) Unilateral supplementary area lesions produced weak, transient grasp reflexes in the contralateral limbs, and within one week moderate bilateral hypertonia of the shoulders. No noticeable paresis was present.

(3) Simultaneous bilateral supplementary area ablations yielded practically no paresis, but posture and tonus were disturbed. Immediately there was increased resistance to passive movements of the limbs, and during an interval from two to four weeks contractures supervened. The hypertonia was encountered in the flexor muscles. The tendon reflexes were hyperactive within a day to two weeks with some of them (finger and toe jerks) becoming clonic. The spasticity demonstrated topographical localization according to the portions of the areas removed. Grasp reflexes were present for three to five weeks.

(4) When the supplementary area was removed bilaterally in two stages with over six months intervening between the operations, only slight increased resistance was located at the ankles. No hyperactive tendon reflexes appeared, and weak, temporary grasp reflexes were observed after the second operation. This indicates that practically no release phenomena will follow the second operation provided a sufficient time interval intervenes between two such operations.

(5) If in addition to a simultaneous bilateral supplementary lesion there occurred unilateral injury of the precentral hind-limb area, the immediate resistance and final contractures were less in the lower limb opposite the additional precentral ablation.

(6) If with removal of the precentral motor area the supplementary area was damaged, there resulted localized increased resistance to passive movement according to the portions of the area encroached upon. This was true with unilateral and bilateral ablations.

(7) The lesion involving unilateral precentral plus supplementary limb areas resulted in immediate hypotonic paresis and impairment of tendon reflexes. This stage of diminished reflex activity within two weeks merged into a state of increased reflex activity; the hypotonus changed to moderate increased resistance to passive movements in the fore-limb and to approximately normal tonus in the hind-limb. The experiment defined the supplementary motor area as concerned with controlling movement, for the paralysis observed was greater than after unilateral precentral motor removals.

(8) The placing and hopping reactions persistently disappeared in the affected extremities following unilateral precentral plus supple-

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mentary lesions; but previous simultaneous or later removal of the limb area of the precentral or of the supplementary motor system in the opposite hemisphere permitted the reactions to be performed crudely in the affected extremity.

(9) Ablation of "area 6" not included in the precentral or supplementary motor area resulted in no motor impairment of the limbs, no grasp reflex, and no hypertonia. This indicates that the only motor functional parts of "area 6" are those portions included in the precentral and supplementary motor area.

ACKNOWLEDGMENTS

I wish to thank Dr. E. M. Larsen for helpful assistance in the preparation of the paper and Dr. R. S. Ostenso for the photography.

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LEGENDS TO PLATES

PLATE XVII

FIG. 2.—Monkey **50–149**. To illustrate one of the postures assumed by the fingers when the elbow was passively extended. The four lateral digits are flexed at the metacarpophalangeal joints and moderately fanned. The thumb is adducted and flexed maximally.

FIG. 3.—A, Monkey **50–149**. Extent of lesions on the dorsal surface of the hemispheres. The left ablation is a little larger in the finger representation of the supplementary area. There is no involvement of either precentral motor area. On the right in the medial part of "dorsal area 6" is a 0·5 × 1·5 mm. lesion. B, Medial views after hemispheres were separated. Supplementary face area is not removed on either side. On the surface the lesions appear as far caudal as wished and seem to be restricted to the supplementary motor area.

PLATE XVIII

FIG. 4.—A, Monkey **50–79**. Dorsal view of lesions. On the right the "dorsal area 6" removal is incomplete medially. The ablation does not involve the precentral motor area. On the left the "dorsal area 6" ablation is larger and more extensive ventrally and extends beyond the anterior limit of the inferior precentral sulcus. The left precentral hind-limb area is severely damaged with removal of the lower trunk and proximal hind-limb representations. B, Dorsolateral surfaces of the hemispheres after separation. The right "lateral area 6" lesion is as intended and extends from the dorsal bank of the Sylvian fissure to the inferior precentral sulcus rostral and lateral to the precentral face area. The left "lateral area 6" lesion is slightly smaller. C, Extent of lesions on the medial surfaces. On the right the supplementary fore-limb is removed but the supplementary face area is intact. From the surface view the right supplementary hind-limb area does not seem disturbed. On the left the lesion undercuts the rostral half of the precentral hind-limb area and includes the entire supplementary face and fore-limb areas. It is not clear how much of the supplementary hind-limb area is destroyed; caudal half is probably still intact. There is also a lesion on the lower bank of the cingulate sulcus at the level of the septum pellucidum.

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PLATE XVIII

FIG. 5.—Monkey 50–19. Dorsal extent of lesions. On the left the entire precentral motor area is removed and the dorsal surface of the sulcus cinguli is ablated, severely damaging the supplementary area. On the right the removal of "area 6" appears far enough rostral, leaving the supplementary limb representations intact.

PLATE XIX

FIG. 6.—A, Monkey 50–70. Dorsal view of ablations. Fore-limb area lesions and left hind-limb area removal appeared as intended. The right hind-limb area lesion does not extend as far rostralward as desired, and the axial musculature portion of the precentral motor area appears intact. In addition, there is a large traumatic lesion of the left occipital lobe situated medial to the centre of the foveal representation. It extends from the sulcus lunatus to the occipital end of the hemisphere in the lateral half of the visual cortex. B, Medial view of hemispheres after separation. The right lesion extends to the cingulate sulcus and involves at least part of the supplementary hind-limb area on the dorsal bank of the cingulate. The left ablation is a little wider anteroposteriorly but does not involve as much of the supplementary hind-limb area on the dorsal bank of the sulcus cinguli. The supplementary face and fore-limb areas appear intact bilaterally.

FIG. 7.—Monkey 50–135. Bilateral removal of dorsal portion of Hines' "strip" area. The lesions appear essentially as intended, the right being slightly more posterior. Medially the left lesion is 14 mm. and the right 12 mm. rostral to the upper end of the central sulcus. Laterally both are 8 mm. rostral to the central sulcus.

FIG. 8.—Monkey 51–29. Dorsal view of ablations. Laterally the lesion does not reach the end of the central sulcus by 2 mm. It touches the inferior precentral dimple and extends half-way down the lower branch of the inferior precentral sulcus. The ablation appears to follow the depth of the central sulcus. On the medial wall it extends about half-way to the cingulate sulcus. The entire precentral hind-limb area probably was not removed, but the supplementary motor area was apparently left intact. The rostral border of the ablation was apparently as intended but it has migrated toward the central sulcus and the whole width of the lesion appears less than at the time of operation.

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PLATE XVII

FIG. 2

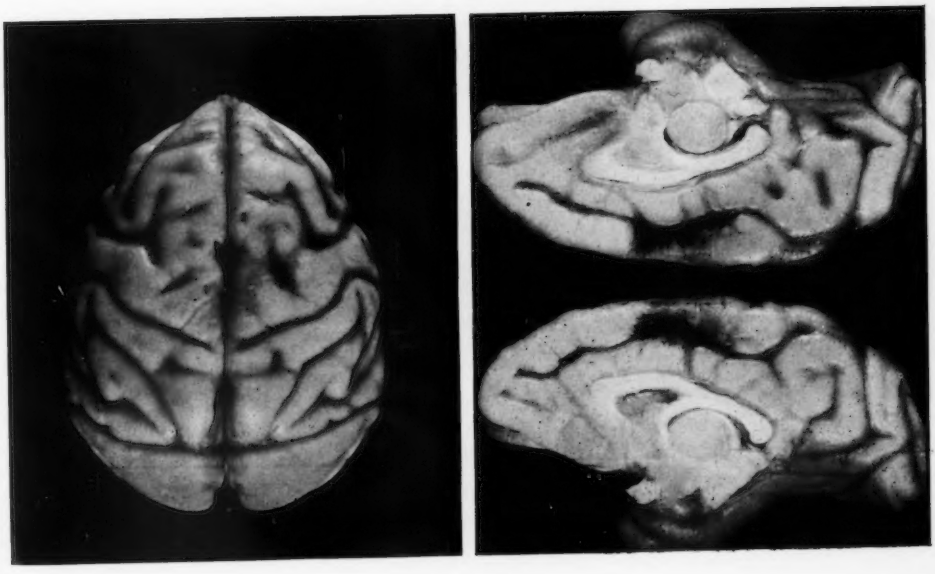

FIG. 3

To illustrate article by Ann Marie Travis.

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PLATE XVIII

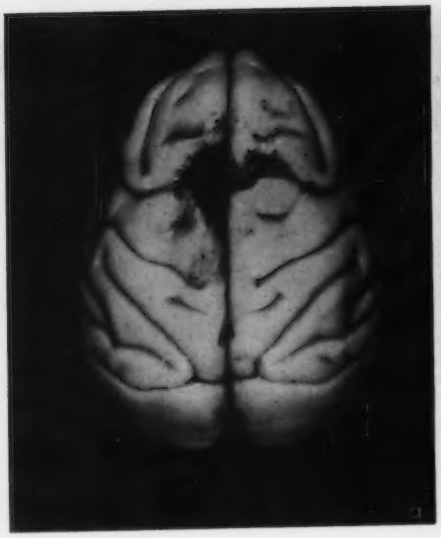

FIG. 4A

FIG. 4B

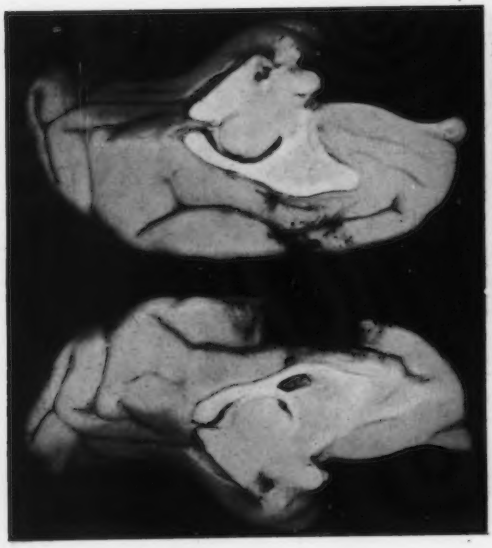

FIG. 4C

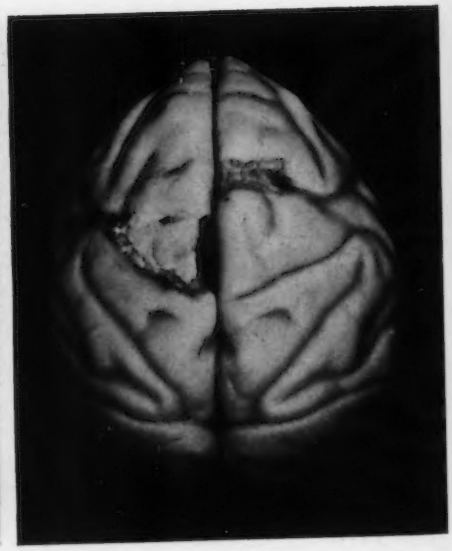

FIG. 5

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PLATE XIX

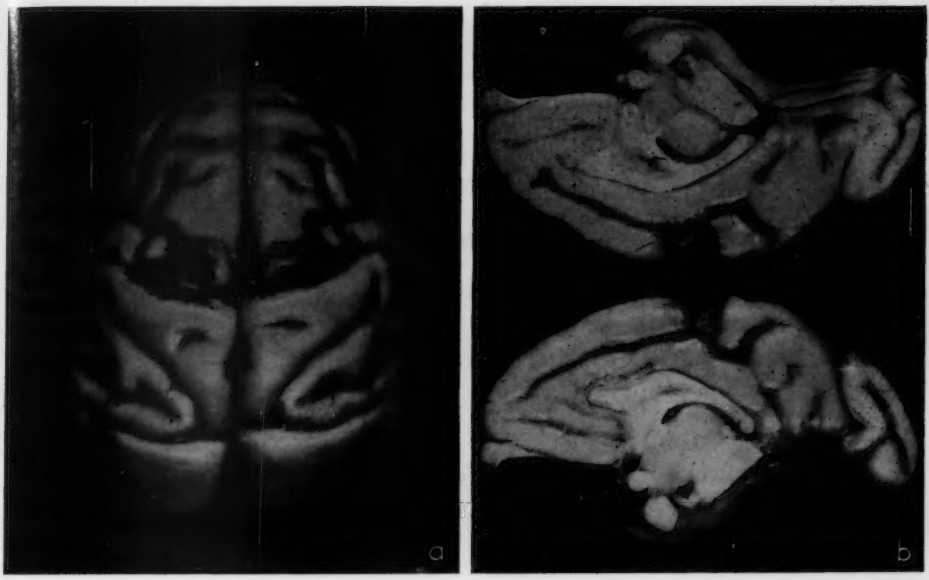

FIG. 6

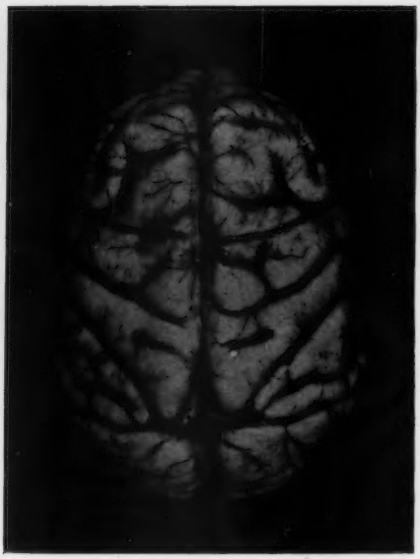

FIG. 7

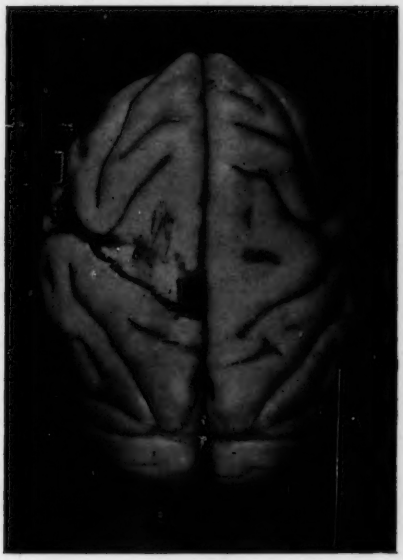

FIG. 8

To illustrate article by Ann Marie Travis.

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UNUSUAL CENTRENCEPHALIC SEIZURE PATTERNS

BY

D. A. HOWELL

(From the Department of Neurology and Neurosurgery, McGill University, and the Montreal Neurological Institute)

INTRODUCTION

EXAMINATION of the records of patients attending the Neurological Institute and Seizure Clinic of the Royal Victoria Hospital, in Montreal, revealed that many of the cases of centrencephalic epilepsy[1] showed unusual patterns of attacks. These seizure patterns differed markedly, at times, from the myoclonic *petit mal, petit mal* automatism, *petit mal* and *grand mal* attacks, which are usually considered characteristic of this form of epilepsy and sometimes they mimicked focal cortical seizures. The results of the clinical study of the unusual seizure patterns shown habitually by a few and occasionally by many of the patients, who fulfilled very rigid criteria of selection, are reported below. There was no evidence of any other disorder of the brain on careful examination in these patients, and their electroencephalograms showed the complete picture of bilaterally synchronous, three-per-second wave-and-spike discharges of classical form, either spontaneously or in response to hyperventilation (Jasper *et al.*, 1947; and Gibbs *et al.*, 1936). (Fig. 1.)

Cases were excluded if the initial rate of discharge was less than three or more than four per second, and if the form of the discharge was not a regular succession of smooth domes and darts. No patients were included in whom this type of discharge had only been obtained after activation with metrazol, and a small group were excluded because they showed an additional cortical focus of epileptic discharge. The practice of surgical treatment of epilepsy over many years in Montreal has attracted patients with unusual seizure patterns and there-

[1]The terminology used at Montreal and described in Penfield's and Jasper's Monograph entitled "Epilepsy and the Functional Anatomy of the Human Brain" (1954), has been used throughout this report. Centrencephalic epilepsy has many other names in other centres, and genuine, idiopathic, essential, cryptogenic genetic, *petit mal* and central epilepsy are the commonest ones used for the same disorder. The characteristic seizure patterns are known by a variety of names, but the Montreal terminology is quite clear in its meaning.

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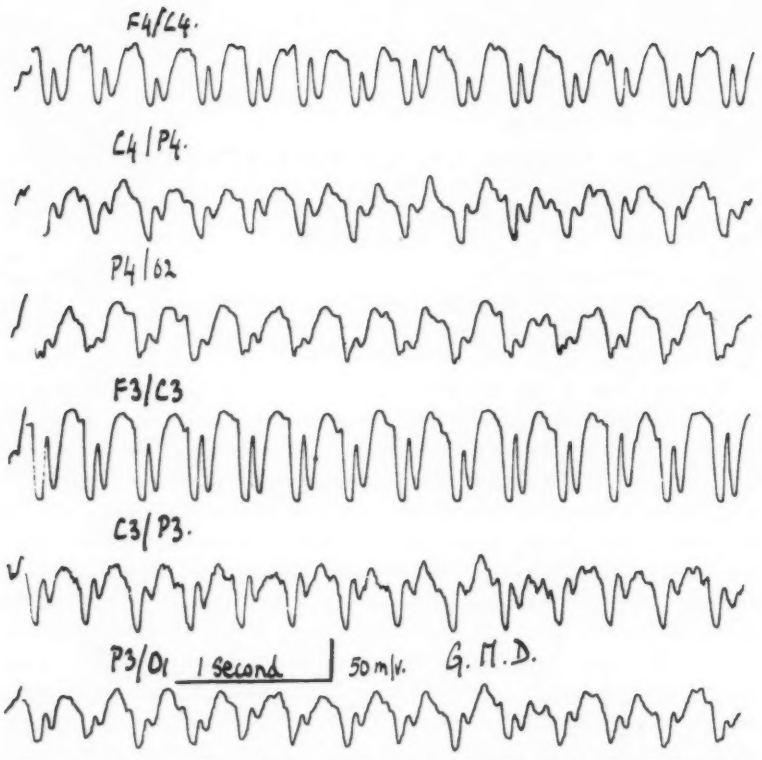

FIG. 1.—An example of 3-per-second wave-and-spike discharge (G. M. D.).

fore it is not possible to assess accurately the true frequency of such cases.

SEIZURES WITHOUT LOSS OF CONSCIOUSNESS OR AMNESIA

The first group is composed of minor seizures in which a variety of motor, sensory, autonomic or psychical disturbances occur, without any profound loss of consciousness or amnesia for the attack. The patients are able to observe, recollect and later describe most of the events which occur in the seizure. These minor seizures are sometimes the prelude or initial phenomena of a major convulsion and occasionally it is only possible to recognize them for what they are, by the ensuing *grand mal*. They have a special tendency to occur as the first seizure and after a change of medication. It has been suggested that they are more frequent in older patients, but it was not possible to confirm or deny this in the present study, as many younger patients were excluded

because they were unable to give reliable accounts of their seizures. They do not as a rule, cause the patient great inconvenience and therefore are not prominent in his complaints. However, about a quarter of the patients who were studied gave a story of this type of attack and in nearly half of these they occurred habitually.

Motor Phenomena

An infinite variety of motor phenomena were encountered in these minor seizures other than the familiar shock-like contraction of a muscle or a group of muscles of myoclonic *petit mal*. Several patients described sudden loss of power in an arm for long enough to drop whatever they were holding. A brief feeling of "being paralysed all over" was described by one patient and another reported sustained tonic flexion of the forearms as a prelude to her first major seizure. Four patients had attacks of bilateral tremulous movement. In one it was confined to the forearms, but in another all four limbs were involved beginning with the right arm. The jerking was so violent that it always threw the patient to the ground if he was standing, though in the other two, a gentle trembling of the whole body did not prevent the patients from standing or even walking.

Case report.—D. S., a schoolgirl of 11, had about forty such attacks after she omitted to take "Tridione." They began as soon as she swung her legs out of bed in the morning, and might continue for up to two hours. She was aware of trembling all over and inability to part her lips. She could only make a humming noise through her closed mouth when she tried to talk, and her lips seemed stuck together when she attempted to kiss her very flustered mother. She managed to walk, wash and dress herself while the seizure continued. Her mother noted that she could not part her lips, blinked continuously, felt cold to touch and looked as if she was shivering.

Five patients reported movement of the head to one side while they were conscious. One patient would push her head back to the midline after it had turned involuntarily to the right. Another patient felt a strong urge to look to the left and at the same time found he was unable to speak. He was conscious of his head turning before a major convulsion.

Case report.—M. K., a woman of 29, had had frequent minor seizures every day since the age of 10, in which her head leaned and turned a little to the right. The attacks were very brief and this was all she noted, though in an attack witnessed by the author, both sides of the mouth twitched. In prolonged seizures the head turned several times and she was unable to speak. In even more prolonged attacks she was also unable to hear conversation, though if her mother called her sharply by name, she would hear this and it would somehow arrest the attack.

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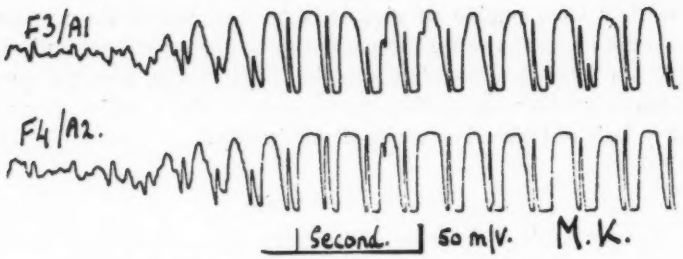

FIG. 2.—EEG of M. K., during a minor seizure.

Another small group of cases described clonic twitching confined to one limb or to one side of the face. In one case the seizure started with the head turning to the left and a drawing up and twitching of the left side of the mouth. This was followed by trembling of the whole body for five minutes without any profound disturbance of consciousness. Another patient had an attack of epilepsy partialis continua, during the first day of treatment with "Tridione." Clonic inversion of the left ankle without any other evidence of a seizure, continued for two hours. This patient always turns to the left in her major convulsions and her left sided hallucinations will be described later.

The ocular phenomena, so common in this form of epilepsy are not always associated with loss of consciousness. No patient actually reported blinking, though it was observed in seizures in which patients remained relatively alert. Three patients were quite aware of staring during their minor seizures and one always referred to these attacks as her "stares." Blurring of vision is not an uncommon complaint and it may well be caused by a paralysis of convergence or accommodation, though this point is unproven.

One patient (G. M. D.) was observed to swallow in a minor attack during which he was conscious of being unable to talk. Chewing movements were seen in another who was, however, unable to recollect his minor seizures.

Sensory Phenomena.

Minor sensory seizures were not as common as motor ones. Three patients reported true vertigo and one a high pitched whistling noise, either as an aura to their major seizures, or as a minor seizure occurring alone. One patient had frequent minor seizures involving blindness, undoubtedly not syncopal, which she called her "blackouts."

Case report.—M. D., a housewife of 23, noted a sudden loss of sight and inability to speak in these attacks. She dropped whatever she was holding and sometimes this was followed by a myoclonic jerk of both hands.

The opinion has already been expressed that the common symptom of blurring of vision may result from a paralysis of accommodation or convergence and not from involvement of the afferent visual pathways. Similarly, the complaint of numbness of one side of the face in two patients, who showed drawing up and clonic movement of this angle of the mouth, may not have represented a true sensory disturbance just as numbness of the face is a common complaint in facial palsy, not accompanied by any loss of sensation.

Autonomic Motor and Sensory Phenomena

Minor autonomic seizures were not rare, either occurring alone or as a prelude to a major convulsion. A sensation of progressive slowing of the heart was reported by one patient and a warm prickling sensation in the head by another. A third noted an epigastric sensation of tightness which rose to her throat to culminate in a choking feeling, while a fourth described a similar attack as a sensation in the epigastrium followed by a feeling of constriction in the chest associated with arrest of respiration for enough seconds to alarm the patient. However, autonomic phenomena were more often reported by observers than by the patients and it is probable that they have been frequently overlooked. Pallor was seen on many occasions. They are frequently seen in *petit mal* and such phenomena as urinary incontinence and drenching perspiration were observed during attacks of unresponsiveness to the environment, which the patients were unable to recollect. Ejaculation of semen occurred habitually during major seizures in one patient.

Psychical Phenomena

A few patients reported vague psychical experiences during minor seizures, which defied their powers of description. One felt as if she was in another world and another was oppressed by a sense of impending death. A third suffered from a "funny faraway feeling." All regarded these descriptions as very inadequate. However, a fourth patient had fairly precise left-sided hallucinations.

Case report.—J. M., a slightly neurotic girl of 25, with a vivid imagination and an excessive childlike fear of death, suffered from minor seizures lasting about two minutes which were sometimes followed by a major convulsion. Her mother recognized these attacks by a sudden onset of facial pallor and clonic blinking. The patient was always able to speak and walk to her bed in preparation for a convulsion. Her description of her mental state during this period has

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varied a little over the years. In 1948, she said she seemed to see a wire fence with a group of children on the other side of it. She seemed to be telling them that she would be coming to them later, though she did not speak out loud. In 1949, she said she felt as if she was being smothered and saw a wall. She seemed to be telling others to go to the other side of it and that she would join them later. In 1953 she described seeing a fence and saying, "Go away." In 1954, she described an almost physical sensation of being pulled towards death, against which she struggled hard. She seemed to see a broad-meshed, silver coloured fence on her left side. She heard voices of people she knew intimately but not always of the same group of people. She was vague about the details of the conversation she held with them, as if the ideas expressed were never properly clothed with words, but the content was similar to that which she described in 1948. The voices asked her where she was going and she replied that she would see them later. Sometimes she saw the people with whom she talked, quite vividly at first, on the far side of the fence, on the left. Later they either faded or walked away; she was uncertain which. This patient always turned to the left in her major convulsions and once had an attack of epilepsia partialis continua in the left foot, described above.

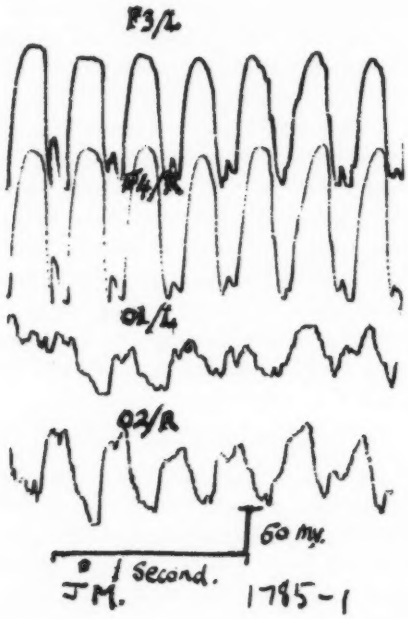

FIG. 3.—Sample of discharge in the EEG of J. M.

SPEECH ARREST

No less than twelve patients clearly recollected being unable to speak during minor seizures. The seizure patterns in three cases (D. S., M. K. and M. D.), have been described above. This phenomenon

cannot easily be attributed to so mild a global disturbance of consciousness, that observation and recall are still possible, except perhaps, in a very young child. The nervous mechanisms subserving speech prove themselves to be much more sturdy in the uncomplicated closed head injury, as these patients are often quite talkative when they are profoundly confused, and later they are totally unable to recollect this period of their illness. It is thought more probable that one or more of the nervous mechanisms subserving speech is paralysed by the discharge in these minor seizures. In a few cases such explanations for the arrest of speech are apparent. D.S. was unable to part her lips during her seizures and clonic movements of the lips were observed in M.K. Another patient was seen to swallow during an attack of speech arrest, an act involving the use of the speech musculature. A fourth patient described arrest of respiration. Strong evidence that aphasic arrest of speech may occur is provided by a patient who was only able to say the word "One" throughout her seizure.

Case report.—A. S., a schoolgirl of 11, came under Dr. A. Elvidge's care because of a few attacks of *petit mal* automatism. His notes are quoted: "When I tested for two point discrimination the patient was only able to answer 'One,' which was apparently due to the fact that she was in a peculiar state of mind, brought about presumably by *petit mal* seizures. She had complete anomia and was unable to give the name of a pencil, etc. She merely answered by saying 'One.' When told to write, she at first looked at the pencil and then wrote her signature perfectly but was unable to read what she had written. The state of anomia and alexia persisted for some 15 to 20 minutes, although she obeyed commands and appeared to understand everything."

If this profound degree of verbal perseveration was due to global confusion, it is unlikely that she would have been able to obey commands and appear to understand everything. In other cases there is only suggestive evidence that the patient may be aphasic.

Case report.—G. M. D., a man of 29, had minor seizures lasting about 15 seconds, in which he was conscious of being confused and unable to speak. Dr. D. Lloyd-Smith witnessed one of these attacks. The patient stood silent and immobile staring ahead. He did not respond, when spoken to. Later he said Dr. Lloyd-Smith's voice sounded blurred and he was unable to grasp the meaning of his words. In another attack he was seen to swallow. A sample of his EEG is shown in fig. 1.

Another patient voluntarily stopped talking in her attacks because she could not understand conversation, though she could hear it quite well. She recognized from the prolonged pauses when some answer was expected from her and many embarrassing experiences had taught her that "yes" was most likely to be appropriate. These two patients who could hear speech but could not understand it, may have suffered

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from aphasic word deafness, but other explanations are possible. Shimazono *et al.* (1953) have demonstrated that the level of consciousness varies greatly during a minor seizure and therefore the powers of observation of some patients may decline in the middle of an attack, being preserved only at the beginning and at the end. In other cases there was no evidence to suggest which of the many possible mechanisms subserving speech was involved in the epileptic discharge. Williams (1953) has likened the total motor arrest which commonly occurs in *petit mal* to the akinetic mute state in which there is an arrest of speech quite distinct from that produced by paralysis of the respiratory or bulbar muscles or the cortical speech mechanisms. A brief, partial akinetic mute state may occur in some of these cases. Often patients state that they have stopped talking in a seizure because they have forgotten what they were about to say. This is a quite distinct phenomenon from being unable to speak, in spite of efforts to do so, and may well be caused by profound confusion in the middle of an attack.

Todd's Paralysis

A second group of unusual seizure patterns, which were encountered in patients with centrencephalic epilepsy, showed a transitory postictal hemiparesis following the major convulsion. Though in only 2 cases were the EEG's entirely satisfactory, another 3 cases were found, who almost certainly suffered from centrencephalic epilepsy. The opportunity to examine these patients immediately after a major seizure does not often arise and the phenomenon may not be so very rare.

Case report.—P. D., a woman of 24, had her second major seizure while in hospital with sciatica. Her head and shoulders turned to the right at the onset of the convulsion which lasted two minutes. Five minutes after the end of the seizure, she exhibited confusion, clumsiness of tongue movements and a right hemiparesis with exaggeration of the right tendon reflexes, absent right abdominal reflexes and a right extensor plantar response. Forty-five minutes later these abnormal physical signs could not be detected. She had no memory for the attack or the postictal weakness.

Case report.—G. B., a man of 23, suffered from major seizures with initial loss of consciousness, in which his head turned to the right, his arms extended in front of him, and his left leg drew up, as he uttered a typical epileptic cry. For the rest of the day, he complained of tiredness and dragging of the right leg when walking.

Discussion

The main purpose of this report is to draw attention to those unusual seizure patterns. The classical accounts of idiopathic or genuine epilepsy of Reynolds (1861), Gowers (1881) and Hughlings Jackson (1884 and 1890) include all these phenomena and many others besides,

but it is possible that the EEG's would have revealed cortical foci in some of their cases. An important conclusion to be drawn from this study is that the seizure patterns of patients with bilaterally synchronous three-per-second wave-and-spike discharges in the EEG, may be as varied as the patterns in the groups of epileptics these authors described.

It was to be expected that a group of seizures would be found, in which the clouding of consciousness was intermediate in severity between larval electroencephalographic seizures, and the apparent loss of consciousness in *petit mal*. It is surprising, however, that so many centrencephalic seizures can be found which closely mimic those arising from cortical foci. Many, though not all of the seizures which have been described, would lead the physician to suspect a cortical focus if no other evidence were available to him, such as family history or accounts of other types of seizure pattern occurring in the same patient. It is possible that the EEG has failed to reveal an additional cortical focus, which may be present in some of these cases. The two types of epileptic discharge have been found in several patients who were discarded from this series. It is possible that the type of discharge shown by patients who mimic focal cortical epilepsy, may be secondary to a low voltage spike focus in some part of the cortex not easily accessible to the electrodes of the EEG. Such cortical foci are often present in cases showing a similar discharge at a rate of less than three per second. At first glance these cases appear incompatible with the theory of central origin of the discharge in this form of epilepsy, but this is not so. Penfield (1951) has described how an epileptic discharge may spread by contiguity into the surrounding grey matter, and also how it may spread by projection along a fibre tract arising in or near the epileptic focus, to a distant collection of nerve cells. If the discharge arises centrally, the spread by contiguity must sometimes be restricted or the patients would become unconscious in all their attacks. The EEG (M. K.) during a minor attack when her head turned and leaned a little to the right, is shown on p. 202. In this case the spread by contiguity must not only be restricted but asymmetrical. Asymmetrical and restricted spread by contiguity in the central areas of the brain, might easily be followed by projection of the discharge to a restricted area of cortex in one hemisphere. This would lead to an attack mimicking a focal cortical seizure. A similar clinical seizure pattern may be produced by discharges in different neuronal pools if they belong to the same system of neurones.

It was hoped that when this study was planned that it might throw some light on the mechanisms involved in centrencephalic epilepsy, but if anything, it seems to have added confusion. However, it will be

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necessary to account for these unusual seizure patterns in any theory purporting to explain the phenomena of this form of the disorder, because they are not rare enough to be totally ignored, or dismissed as coincidental.

Summary

(1) Minor motor, sensory, automatic and psychical seizures are described in which the patients suffered little impairment of consciousness or amnesia for the attack, intermediate in severity between larval electroencephalographic seizures and *petit mal*. The patients showed bilaterally synchronous, three-per-second, wave-and-spike discharges in the EEG.

(2) The mechanisms involved in speech arrest in such attacks are discussed.

(3) Two cases with transitory hemiparesis after their major seizures, who also showed this type of EEG discharge are described

(4) Several possible explanations of the resemblance of these attacks to focal cortical seizures are offered.

(5) It will be necessary for any hypothesis purporting to explain this form of epilepsy to account for these unusual seizure patterns.

Acknowledgments

I wish to acknowledge much helpful criticism I have received from Dr. Francis McNaughton and Dr. Wilder Penfield and also Dr. Herbert Jasper's advice in selecting the patients, whose EEG's were all taken in his laboratory. This work was completed with the assistance of a Public Health Research Grant from the Department of National Health and Welfare, Ottawa.

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BELL'S PALSY

A Clinical and Electromyographic Study

BY

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Sir Charles Bell in his book entitled "The Nervous System of the Human Body" (1844) refers to about forty examples of paralysis of the facial muscles from a variety of causes which include ear disease, trauma, parotid-gland disease, syphilis and intracranial tumour. In some patients there was an association with pregnancy or a history of exposure to cold and in one the paralysis was accompanied by pain, hyperacusis and disturbance of taste on one side of the tongue.

Later in the nineteenth century it became customary to refer to all forms of facial paralysis as "Bell's palsy" but more recently this term has usually been restricted to those patients in whom the paralysis results from an intrinsic lesion of the seventh cranial nerve (Cawthorne, 1951*a*), and it is so used in this paper. An extensive literature on facial paralysis has accumulated and Duel (1933) stated that 1829 publications on the subject existed at that time. The literature can be dealt with under the headings of (1) Ætiology; (2) Prognosis; (3) Treatment; (4) Sequelæ.

(1) *Ætiology*.—It has long been known that many examples of facial paralysis are not due to involvement of the facial nerve by any demonstrable extrinsic lesion and Fuchs (1907) stated that 500 of the 600 patients he studied were suffering from "idopathic" facial paralysis. Post-mortem studies are very rare but Minkowski (1892), Dejerine and Theohari (1897) and Mirallié (1906) described the changes of a parenchymatous peripheral neuritis affecting the distal branches of the facial nerve in patients who had suffered from facial paralysis of this clinical type. These findings seem to have been largely forgotten and many other ætiological hypotheses have been presented. Among these may be mentioned emotional shock (Fenwick, 1909), nervous predisposition (Bernhardt, 1892*a*), compression from œdema of the intratemporal portion of the nerve (Clark, 1907; Hall, 1951; Kettel, 1947), spasm of the vasa nervorum (Audibert, Mattei and Paganelli, 1936), "infection"

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(Merwarth, 1949), herpes zoster (Fraser, 1904; Hunt, 1910; Aitken and Brain, 1933), endogenous toxins (Orbison, 1907) and neuritis or irritation of the great auricular nerve spreading to the facial nerve (Wyburn-Mason, 1954).

(2) *Prognosis.*—There is little evidence that the prognosis in Bell's palsy is related to age, to sex or to initial manifestations such as pain, loss of taste or herpes (Bernhardt, 1892*b*; Waterman, 1909), but Findlay (1950) claimed that facial paralysis associated with herpes zoster always recovers rapidly. There is fairly general agreement that the majority of patients suffering from Bell's palsy recover completely within two or three months (Duel, 1934; Cawthorne, 1951*b*; Martin, 1952). In the minority the nerve fibres are so damaged that denervation of the facial musculature occurs and the subsequent recovery by re-innervation is a protracted process. Study of the electrical reactions has long been regarded as a safe and objective method of detecting the presence of denervation of the facial muscles (Gowers, 1893; Hoffmann, 1894) but more recently doubt has been expressed about its reliability (Cooksey, 1941; Kettel, 1947) although Park and Watkins (1949) claim considerable, but not complete, accuracy for the method. Modern electromyography (Weddell, Feinstein and Pattle, 1944; Bauwens, 1948) is a more accurate method of detecting denervation, and Collier (1949) claims that it is reliable in assessing the prognosis in facial paralysis, but no quantitative study has been published.

(3) *Treatment.*—The early detection of those patients who will recover rapidly and completely is of particular importance in assessing the results of treatment. Electrical stimulation of the facial muscles is commonly used, but its value has never been accurately established. Surgical treatment by means of decompression of the facial nerve in the stylomastoid (fallopian) canal has often been advocated (Ballance and Duel, 1932; Sander, 1934; Tumarkin, 1936; Tickle, 1945; and Cawthorne, 1952) but no controlled study has ever been made. The same objection can be made to other suggested forms of treatment such as short-wave diathermy (Bourbon, 1937), dehydration (Audibert, *et al.*, 1936), injections of T.A.B. vaccine (Stannus, 1933) stellate ganglion block (Swan, 1952), antibiotics (Gitlin, 1953), histamine injections (Skinner, 1950), cortisone (Rothendler, 1953; Robison and Moss, 1954) and mechanical support (Jaeger, 1919; and Allen and Northfield, 1945). In a controlled trial of the influence of cortisone on the incidence of denervation in Bell's palsy, no effect was demonstrated (Taverner, 1954).

(4) *Sequelæ.*—There is also confusion about the long-term effects of

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denervation of the facial musculature. The commonest sequelæ are contracture of the facial muscles, associated movements of one part of the face on voluntary movement of another part and so-called "spontaneous" twitching of the face. Surprisingly little is known of their severity and frequency but it is generally agreed that they never disappear (Lipschitz, 1906; Petz, 1933). Earlier writers attributed these sequelæ to changes in excitability of the VII nucleus resulting from retrograde changes in the cell bodies secondary to the nerve lesion (Hitzig, 1872; Bernhardt, 1892*b* and Remak, 1898). Lipschitz (1906) contended that misdirection of the regenerating axones was responsible for associated and spontaneous movements. This view was endorsed by Spiller (1919) and confirmed by the experimental studies on monkeys of Howe, Tower and Duel (1937) but Wartenberg (1946) argued at length that nuclear changes are responsible.

A less common sequel to Bell's palsy is the "crocodile tear" phenomenon or paroxysmal unilateral lacrimation on eating (Kaminsky, 1929; Ford, 1933). Its incidence is uncertain. Russin (1939) stated that only eight examples had then been described but James and Russell (1951) found it six times in 28 patients with denervation of the facial muscles. The phenomenon is thought to result from the misdirection of regenerating axones at the site of the lesion (Ford and Woodhall, 1938) but Chorobski (1951) postulates interaction of nerve fibres due to myelin sheath defects at the site of the lesion.

The present communication stems from a personal clinical and electromyographic study of 100 consecutive patients suffering from Bell's palsy. The prognostic value of electromyography is quantitatively assessed and some of the sequelæ of denervation are analysed clinically and electrically. The findings suggest that some theories about Bell's palsy require revision.

Material and methods.—The patients were seen in the electromyographic department of the Leeds General Infirmary and were diagnosed as suffering from Bell's palsy on the basis of these three criteria: (1) Complete or partial paralysis of the muscles of expression of the whole of one side of the face of sudden onset. (2) Absence of any symptom or sign of any other disease of the central nervous system. (3) Absence of any symptom or sign of any disease of the ear or posterior fossa. They were examined clinically and electrically during the course of their disorder. The degree of paralysis was estimated visually as a percentage of the function of the normal side. This method proved reasonably consistent from visit to visit but was supplemented by still

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photography under standard conditions in many patients. The figures for degree of recovery in Table II were obtained by halving the summed estimations for the frontalis and orbicularis oris muscles.[1]

The electrical examination consisted of concentric needle electrode exploration of the facial muscles without local anaesthesia. The electrical activity was amplified by a double channel amplifier and presented on a double channel oscilloscope and through a loud speaker. The amplifiers were of conventional design with battery driven direct coupled push-pull pre-amplifiers condenser coupled to direct coupled main amplifiers. Permanent records were obtained with a Cossor camera (model 1428). In some patients supplementary studies of neuromuscular excitability were made with a Ritchie-Sneath stimulator.

Special attention was paid to the detection of fibrillation activity (fig. 1) which indicated that the nerve supplying the muscle had degenerated (Weddell *et al.*, 1944). A normal muscle at rest is electrically silent but once denervation has occurred spontaneous activity appears. This consists of short duration (1 msec), small amplitude (50-150 μV), potentials which produce a characteristic clicking sound in the loud speaker. Fig. 1 shows typical fibrillation activity at rest from two

FIG. 1.— Needle electrode recordings from the resting facial muscles showing fibrillation activity. A, ♀, 46 years, four weeks after onset of Bell's palsy. B, ♂, 59 years, three weeks after onset. Calibration, A, 100 μV. B, 250 μV. Time-marker 10 msec. in this and all subsequent electrical records except fig. 8.

patients with Bell's palsy of four weeks' duration (1A) and three weeks' duration (1B). Those patients in whom fibrillation was detected were classified as "failures," the remainder as "successes," with seven exceptions mentioned later.

[1]The term orbicularis oris is used in a general sense for the complex of muscles round the angle of the mouth.

Findings

(1) *The patients.*—100 consecutive patients with Bell's palsy who had attended the electromyographic department of the Leeds General Infirmary were examined, with the exception of 6 patients who could not be traced. They were all re-examined for the purposes of this investigation during the summer of 1954. 29 patients were originally examined within one week from the onset of the facial paralysis, 44 within two weeks and 74 within three weeks. There were 57 females and 43 males and their ages ranged from 3-78 years (mean 42 years) (Table I). The facial paralysis was left-sided in 56 and right-sided in 44. The paralysis was clinically and electromyographically complete, with no motor units under voluntary control, in 28 patients when first seen. Pain around the ear was present at or before the onset of the paralysis in 50 patients, and there was subjective disturbance of taste sensation in 44 patients. Both symptoms were present in 22 patients. Herpes zoster vesicles were detected in the external auditory meatus of 9 patients.

Table I.

	Total	*Successes*	*Failures*
Number	100	45	55
Sex	57 F 43 M	26 F 19 M	31 F 24 M
Age	3–78 years (mean 42)	3–76 years (mean 40)	13–78 years (mean 44)
Side	56 L 44 R	21 L 24 R	35 L 20 R
Complete palsy	28	3	25
Pain	50	19	31
Taste	44	20	24
Herpes zoster	9	4	5

Symptoms and signs in Bell's palsy. Complete palsy means no motor units under voluntary control on electromyographic examination. Taste refers to subjective disturbance of taste.

(2) *Successes.*—45 patients recovered rapidly and completely and were classified as successes. In 44 of these patients no evidence of denervation—fibrillation activity—was found and a good prognosis was given. In one patient a technical defect led to a mistaken finding of "scanty fibrillation activity" and a doubtful prognosis was given. This patient began to recover in about fourteen days and was completely normal within three months. She was therefore classified as a success.

The successful group consisted of 26 females and 19 males, aged 3-76 years (mean 40 years) (Table I). The facial palsy was left-sided

in 21 patients and right-sided in 24 patients. When first seen the paralysis was clinically and electromyographically complete in 3 and incomplete in 42 patients. 19 patients complained of pain in and behind the ear, sometimes spreading to the neck, for a few days before, or at the onset of, the facial palsy. 20 patients admitted to a subjective disturbance of taste sensation on the same side of the tongue as the facial palsy, and in 9 both the pain and the disturbance of taste were present. In 4 patients herpetic vesicles were noted in the external auditory meatus.

An attempt was made to estimate the times of onset of recovery and of total duration of the facial palsy, although such estimates are necessarily approximate (Table II). In the successful group of patients

TABLE II.

	Total	*Successes*	*Failures*
Number	100	45	55
Fibrillation	50	1 (?)	49 (+2?)
Electrical treatment	29	3	26
Onset of recovery	—	3–21 days (mean 11)	7–180 days (mean 70)
Total duration	—	18–150 days (mean 51)	—
Voluntary movement			
100 per cent	—	45	0
75–100 per cent	—	0	18
25–75 per cent	—	0	16
25 per cent	—	0	21
Associated movements	55	0	55
"Spontaneous" movements	55	0	55
Contracture	36	0	36
Crocodile tears	6	0	6

Recovery from Bell's palsy. Denervation means fibrillation activity detected on electromyographic examination. Electrical treatment was galvanism, usually three times weekly. Figures for onset of recovery and total duration are approximations.

recovery began in from 3-21 days (mean 11 days) from the onset of the paralysis. The total duration of the paralysis was 18-150 days (mean 51 days) but in only 2 patients did the condition last for more than 90 days. 4 of these patients were treated by electrical stimulation and the duration of paralysis in this sub-group was 35-90 days (mean 50 days).

(3) *Failures*.—The remaining 55 patients were classified as failures. None of them has recovered completely in periods of six months to three and a half years (mean 1·7 years) from the onset. In 49 of these patients profuse fibrillation activity was detected by needle electromyography and a poor prognosis was given. In patients seen sufficiently early, profuse fibrillation activity was usually detected by the seventh to the tenth days. In some patients scanty fibrillation potentials were detected

as early as the fourth day, becoming profuse after seven days. Occasionally, electrical evidence of denervation was not detected until three weeks after the onset. In two patients the presence of fibrillation activity was uncertain, probably because of observer error, and an unjustifiably favourable prognosis was given. The course of the condition, with slow improvement and the development of associated movements, showed that denervation had, in fact, occurred and these patients were classified as failures. Four patients were seen so late in the illness that it was obvious that denervation had occurred, because of contracture formation and associated movements. In these patients fibrillation activity was not detected.

The age, sex and clinical features of the failure group did not differ significantly from the success group (Table I). There were 31 females and 24 males with ages ranging from 13-78 years (mean 44 years). The facial palsy was left-sided in 35, and right-sided in 20, patients. Among those patients seen sufficiently early in the disorder, the paralysis was electromyographically complete in 25 and partial in 12. There was a complaint of pain in 31, of disturbance of taste in 24, and of both together in 13, patients. Herpetic vesicles were observed in 5 patients. Voluntary movement began to return in 7-180 days (mean 70 days) but none of this group has yet recovered completely (Table II). 26 of the "failure" group were treated by electrical stimulation without any apparent effect on the course of the disorder. No relationship was found between electrical treatment and the development of contracture of the facial muscles.

(4) *Sequelæ*.—There were no sequelæ in the 45 patients in the "successful" group. The sequelæ investigated in the "failure" group were: (*a*) Incomplete return of voluntary movement. (*b*) Contracture formation. (*c*) Associated movements. (*d*) "Spontaneous" movements. (*e*) Crocodile tears. The incidence of these sequelæ is given in Table II. 21 of the patients showed less than 25 per cent recovery of voluntary power, 16 had recovered between 25 per cent and 75 per cent of normal power and 18 had more than 75 per cent of normal power, although none were regarded as being completely normal. If the 42 patients who had been observed for more than one year are analysed the figures are 17 with less than 25 per cent recovery, 11 between 25 per cent and 75 per cent and 14 with more than 75 per cent recovery. Contracture formation, as shown by abnormal depth of the naso-labial fold, or narrowing of the palpebral fissure, with the face in repose, was found in 36 of the 55 patients. Some degree of associated movement, that is, involuntary contraction or over-action of one part

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of the face during voluntary contraction of another part, was seen in every one of the 55 patients after denervation of the facial muscles. Similarly, every patient showed spontaneous movement of the musculature around the mouth on blinking, although in some it was very slight and could only be detected by a very careful examination. The crocodile tear phenomenon was present in 6 patients. In five the tears ran down the cheek, while in the sixth there was a complaint of excessive fluid in the nose on the affected side when eating.

There was no relationship between the degree of recovery of voluntary power, contracture formation, and the presence of associated movements. This is illustrated in figs. 2–6 (Plates XX to XXIV). Fig. 2A shows the symmetrical face in repose of a 49-year-old woman three years after the development of complete right facial paralysis. The onset of improvement was so gradual that it was difficult to set a time for it, but it was between three and six months after the onset of the paralysis. Fig. 2B and 2C show almost complete lack of voluntary movement of the frontalis and orbicularis oris muscles and the eye-lids cannot be fully closed (2D) but there is no sign of contracture formation. There is some associated movement of the lower face on eye closing as is shown by the dimpling at the right angle of the mouth and the right side of the chin (2D). It is important to note that the pattern of chin-dimpling on eye closure (2D) is different from that which develops when she raises her eyebrows (2B) or shows her teeth (2C). Twitching of the dimpled areas in fig. 2D was found to be synchronous with blinking.

Fig. 3A shows the face of a 52-year-old woman two years after the onset of left facial palsy with subsequent denervation. There is a marked contracture of the left zygomaticus major muscle but the palpebral fissure is wider on the left than on the right. Attempted contraction of the left frontalis (3B) and left orbicularis oris (3C) muscles shows that little voluntary activity is present but there is narrowing of the left palpebral fissure on showing the teeth. The eye can be well closed (3D) but there is an associated movement of the angle of the mouth and the chin on the same side. The amount of movement of the left angle of the mouth during eye closure is clearly greater than the degree of voluntary control of that region. The pattern of dimpling of the chin is quite different in figs. 3B, 3C and 3D. There was twitching of the muscles around the left half of the mouth synchronous with blinking.

Fig. 4A shows an apparently normal boy of 13 one year after an attack of right Bell's palsy with subsequent denervation. There is no sign of contracture but figs. 4B, 4C and 4D show defective voluntary

power of the right face. The most striking feature is the associated movement of the right angle of the mouth and chin on raising the eyebrows (4B), of the eyelids on showing the teeth (4C) and of the mouth and chin on closing the eyes (4D). The pattern of associated movement varies strikingly in relation to the voluntary movement which is in train. There was much twitching of the right lower face on blinking.

In fig. 5 is illustrated the face of a man aged 36 two years after an attack of right facial paralysis with subsequent denervation. There is no contracture formation and little deficit of voluntary movement except at the angle of the mouth (5C). Associated movements are present, such as narrowing of the palpebral fissure on showing the teeth (5C) and furrowing of the right lower face on eye closure (5D). There was slight twitching of the right lower face synchronous with blinking.

Fig. 6 shows a girl of 15 eight months after an attack of left-sided Bell's palsy which led to denervation of the facial musculature. Figs. 6A, 6B, 6C show almost complete recovery of voluntary power but there is a well-marked associated movement of the left angle of the mouth and of the chin on eye closure (6D). There was twitching at the angle of the mouth and at the chin synchronous with blinking.

Twitching of the facial muscles was seen, to some degree, in every patient in whom denervation had occurred. It bore no relation to the degree of return of voluntary movement nor to the presence of contracture but it never appeared until some degree of recovery had set in. The earliest onset of twitching of the face in this series was three months. Occasionally it preceded the appearance of any definite voluntary contraction at the site of the twitch. It is sometimes difficult to decide by visual inspection whether the twitching is synchronous with blinking but if a needle electrode is inserted into the twitching area the loudspeaker emits a characteristic sound every time the patient blinks and the decision is simple.

A record of this phenomenon is shown in fig. 7 which was taken from a 38-year-old woman with right Bell's palsy of six months' duration. The upper beam of fig. 7A is an electro-mechanical record of blinking obtained by letting the upper eyelashes strike a metal electrode in front of the right eye at the level of the pupil. The initial, larger, complex, disturbance of the base-line represents eye-closure and the small double beat about 1/10 sec. later represents eye opening. The lower beam is an electromyogram of the right orbicularis oris muscle using a needle electrode. When the patient blinks the upper beam is disturbed when the eyelash strikes the electrode and a single motor unit action potential appears on the lower beam. The motor unit fires

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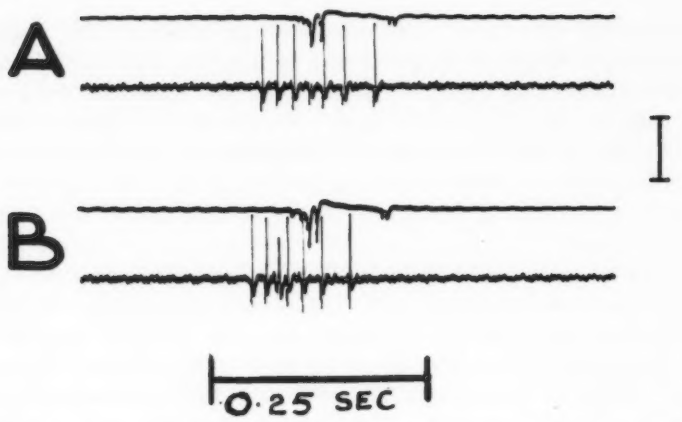

FIG. 7.—♀, 38 years. R. Bell's palsy of six months' duration. Simultaneous electro-mechanical records of blinking (upper beams) and electromyographic records of motor unit activity in the R. orbicularis oris muscle (lower beams). A and B taken under identical conditions several minutes apart. For details see text. Calibration, 250 μV.

six or seven times at a rate of about 50/sec. This electrical activity was accompanied by a visible and palpable twitch at the angle of the mouth. If the blink and the twitch are synchronous it is to be expected that the motor unit activity should slightly precede the disturbance of the upper beam which is produced by the movement of the eyelid when it has already covered about half its course. Fig. 7B is another record from the same patient some minutes later to show that the phenomenon varies little. It is proposed to refer to this type of electrical activity occurring synchronously with blinking as the "blink-burst."

Blink-bursts were found in all the 55 patients in whom denervation had occurred. Sometimes the activity was obvious and widespread; even the ear would twitch in time with blinking. In other patients the blink-burst was associated with the faintest possible dimpling of the chin or lip due to the activity of a single motor unit. Fig. 8A shows a blink-burst recorded from the left orbicularis muscle of a 39-year-old patient who had developed left facial paralysis, with subsequent denervation of the facial muscles, one year previously. In this patient a single motor unit fires at about 50/sec. during blinking. The lower beam shows an almost normal interference pattern of motor-unit activity recorded from the same site when the patient showed his teeth voluntarily.

Another type of blink-burst consisting of a few motor units which

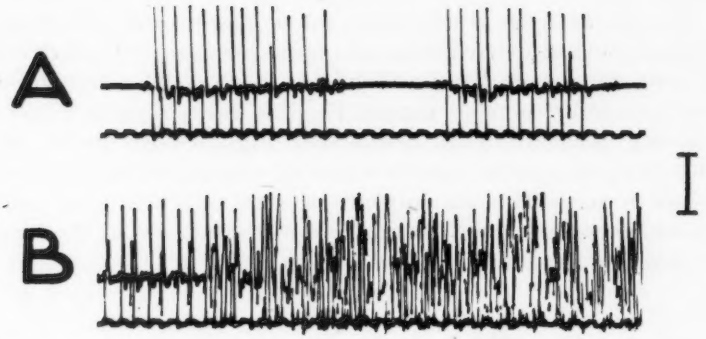

FIG. 8.—♂, 39 years. L. Bell's palsy of one year's duration. Needle electrode recordings from L. orbicularis oris muscle. A, Two successive blink-bursts involving a single motor unit. B, Interference pattern of full voluntary contraction at the same site. Calibration, 0·5 mV.

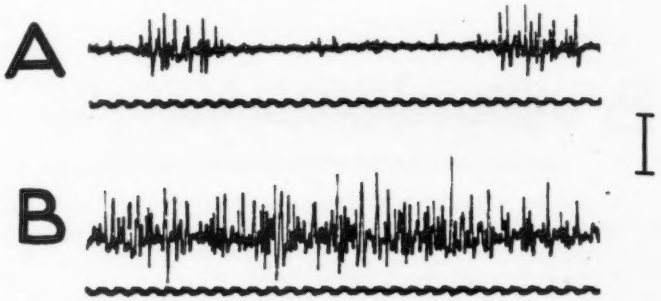

FIG. 9.—♂, 49 years. L. Bell's palsy of eight months' duration. Needle electrode recordings from L. orbicularis oris muscle. A, Two successive blink-bursts involving motor units. B, Defective interference pattern of full voluntary contraction at the same site. Calibration, 250 μV.

fire more or less together during blinking is shown in fig. 9A. This record was taken with a needle electrode in the left orbicularis oris muscle of a 49-year-old patient eight months after the onset of left facial paralysis with subsequent denervation of the facial muscles. Fig. 9B shows the much decreased but fairly well-sustained pattern of motor-unit activity at the same site, when the patient shows his teeth voluntarily. Fig. 10A shows a third type of blink-burst in which numerous motor units fire during blinking but the pattern of voluntary motor-unit activity at the same site is both decreased and poorly sustained (10B). These records were taken from the left orbicularis oris muscle of a 54-year-old patient who, eighteen months earlier, had developed left facial paralysis, with subsequent denervation.

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The records in fig. 11 taken from the right orbicularis oris muscle of a patient who had suffered from right facial paralysis, with denervation, for three years, show that the blink-burst involves different motor-units from those under voluntary control. Fig. 11A shows a typical blink-burst consisting, probably, of two motor-units. Fig 11B shows discrete motor-unit activity on maximal possible voluntary contraction when attempting to show the teeth. The voluntary contraction is maintained but on blinking the motor-units in fig. 11A are clearly superimposed on the record of voluntary contraction.

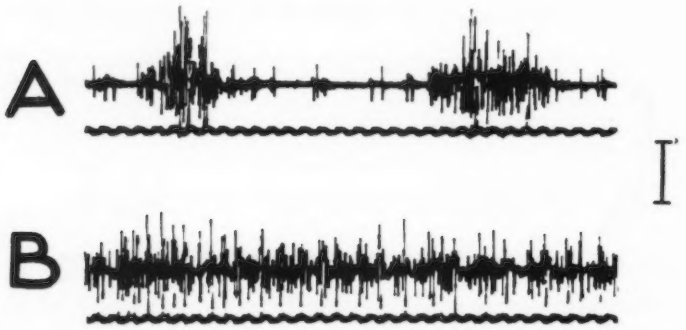

FIG. 10.— ♂, 54 years. L. Bell's palsy of eighteen months' duration. Needle electrode recordings from L. orbicularis oris muscle. A, Two successive blink-bursts involving many motor units. B, Defective interference pattern of full voluntary contraction at the same site. Calibration, 0·5 mV.

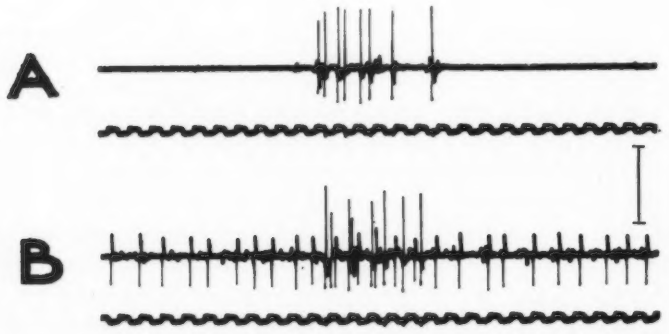

FIG. 11.—♀, 49 years. R. Bell's palsy of three years' duration. Needle electrode recordings from L. orbicularis oris muscle. A, Blink-burst involving two motor units. B, Single motor unit responding on maximal effort with blink-burst potentials superimposed. Same needle position as A. Calibration, 1 mV. (Same patient as fig. 2).

Blink-bursts were always associated with a visible and palpable twitching of some part of the face. With one exception this was the only type of "spontaneous" movement seen after denervation of the facial musculature in Bell's palsy. The exception was an emotional woman aged 49 who had suffered from left Bell's palsy for nearly two years. There was partial recovery of voluntary movement of the face, slight contracture formation at the left angle of the mouth and well marked associated movements and blink-bursts. In addition there was continuous fine irregular twitching of the skin below both eyes and of the left chin. The activity around the eyes resembled "myokymia" but electromyographically only irregular spontaneous motor-unit activity could be elicited and none of the grouped motor-units described by Denny-Brown and Pennybacker (1938) were seen. The spontaneous movement at the angle of the mouth was similar in appearance to that beneath the eyes but it was not possible to demonstrate synchronous firing of motor-units in the two areas with certainty.

Discussion

The results of this investigation show that modern electromyography provides an accurate guide to the prognosis in Bell's palsy. 96 patients were examined before the outcome was certain and 93 of them were correctly divided into those with evidence of denervation (49) and those without (44). The 3 patients in whom difficulty arose were wrongly classified because of observer error, partly through relying on misleading strength-duration curves, instead of repeating electromyography, daily if necessary, until doubt had disappeared.

The 44 patients without electromyographic evidence of denervation all recovered completely in an average time of fifty-one days. Only one mistake was made in assessing the prognosis of patients without denervation. In 49 patients electromyographic evidence of denervation was found and none of these patients has yet recovered completely up to three years after the onset. Two mistakes were made in prognosis in this group. It was noted that electromyographically complete facial paralysis was more commonly followed by denervation (25 out of 51 patients) than by spontaneous recovery (3 out of 45 patients) but no other prognostic criteria of value were found. The incidence of herpes zoster was almost the same in the successful group (4 out of 45) as in the failure group (5 out of 55) which disposes of Findlay's (1950) contention that herpetic facial palsy always recovers completely.

It is evident that complete recovery must be extremely rare after denervation has set in. Nearly a third of the patients with denervation

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of the facial muscles recovered more than 75 per cent of normal voluntary power and a few were practically normal but there was some degree of associated movement and of what are here called blink-bursts in every patient after denervation, which agrees with findings of Lipschitz (1906) and Petz (1933). Contracture-formation was seen in 36 of the 55 patients after denervation but varied considerably in degree. Many patients in whom little power had returned were satisfied with their condition because limited contracture formation had restored their facial symmetry. In general 28 of the 55 patients with incomplete recovery after denervation were satisfied with the outcome of the illness, a finding which casts doubt on the validity of follow-up studies of facial palsy patients based on the results of questionnaires (Müller, 1952).

The only constant sequels to denervation of the facial muscles were the development of varying degrees of associated movement of the face and blink-bursts. Lipschitz (1906) gave a most satisfactory explanation of these phenomena on the basis of branching of the regenerating axones with misdirection of one branch into a "foreign" axone sheath leading to a different part of the face. A single anterior horn cell discharge then simultaneously innervates two separate areas of the face. This hypothesis received powerful support from the experimental studies of Howe *et al.* (1937) in the monkey. They showed that tics related to semi-purposive movements of the face developed after section and suture of the facial nerve in monkeys and they obtained physiological and histological evidence that branching and misdirection of regenerating fibres were responsible.

In spite of this evidence, alternative hypotheses are still current and Wartenberg (1946) has argued strongly that such movements are due to changes in excitability of the cells of the seventh nucleus leading to synchronous firing. One observation put forward in support of this theory is the fact that peripheral cuts on the cheek, allegedly involving distal branches of the facial nerve, may be followed by twitching of the area distal to the cut, synchronous with blinking (Bittorf, 1931). It is argued that this cannot be due to misdirection of regenerating fibres into axone sheaths which leave the parent nerve far proximal to the site of the lesion and must therefore indicate a change in nuclear excitability. Another explanation is, however, possible. Figs. 12 and 13 (Plates XXV and XXVI) show photographic records of a man aged 41 years who had sustained two small scars of the right cheek (13A) at the age of 11. With every blink there was well-marked twitching of the right cheek (13A and 13B), as described by Bittorf (1931) and Wartenberg (1946). Fig. 12 shows evident deepen-

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ing of the right naso-labial fold, compared with the left, and widening of the right palpebral fissure. It seems probable that scar tissue has connected the scars of the original wounds with the outlying fibres of the orbicularis oculi muscle and that the facial twitching in this patient is mechanical in origin.

It can also be argued that the post-paralytic associated movements are due to "a focus of irritation" at the site of the lesion or, more precisely, to cross-excitation of fibres at the site of the lesion resulting from myelin sheath defects (Alajouanine, Thurel and Albeaux-Fernet, 1934). This is comparable to the ephaptic stimulation studied experimentally by Arvanitaki (1942) and Granit, Leksell and Skoglund (1944). Explanations involving changes in nuclear excitability or cross-stimulation at the site of the lesion all imply an existing anatomical connexion between a nuclear motoneurone and muscle-fibres organized into a motor-unit at the site of the twitch. The same motor-unit would be involved in voluntary contraction of the area and, by cross-excitation, in the twitch. This seems improbable in view of the lack of relationship between the degree of return of voluntary power and the degree of associated movement and twitching, in view of the different skin patterns of dimpling produced by voluntary contraction and different types of associated movement (figs. 2–7) and in view of the striking constancy and persistence of the movements. More convincing proof is provided by fig. 11 in which it is clear that separate motor-units are concerned in the blink-burst and in voluntary contraction. The present findings thus confirm the conclusions of Lipschitz (1906) and Howe *et al.* (1937).

Spontaneous bursts of motor-unit activity similar to those shown in figs. 7 and 8 have previously been described and were regarded as being related in some way to the presence of contracture (Richardson, 1951, 1952). In the present investigation this type of activity was only seen in relation to blinking and bore no relationship to the presence of contracture. Contracture was found to be associated with the continuous low frequency firing of single motor units with no recognizable pattern. It is evidently due to sustained contraction of the facial musculature, especially zygomaticus major, and this accords with the old observation of Marinesco, Kreindler and Jordanesco (1931), that novocain block of the facial nerve abolishes contracture.

The crocodile-tear phenomenon occurred in 6 of the 55 patients with denervation, an incidence of approximately 12 per cent. This is approximately half the incidence reported by James and Russell (1951) but the criteria of "failure" are possibly more exacting in the present study. Ford and Woodhall (1938) state that the phenomenon only occurs after

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facial paralysis due to herpes zoster but in the present series none of the affected patients had shown any evidence of herpetic eruptions. All authorities agree that the crocodile-tear phenomenon results from branching and misdirection of regenerating axones, except Chorobski (1951) who attributes it to cross-stimulation from defective myelin sheaths at the site of the lesion. This hypothesis has been shown to be untenable as an explanation of associated movements and cannot, therefore, be accepted as the basis of the crocodile-tear phenomenon. It is important, however, to realize that whatever the mechanism, crocodile tears must result from a lesion proximal to the geniculate ganglion and distal to the facial nerve nucleus.

The various sequelæ of denervation after facial paralysis, with the possible exception of contracture formation, can best be explained on the basis of branching of the regenerating fibres with misdirection of the branches into "foreign" axone sheaths. The fact that facial paralysis in association with herpes zoster may be followed by associated movements (q.v.) is not incompatible with this explanation in view of the histological evidence of Denny-Brown, Adams and Fitzgerald (1944) that in one such patient there was a "motor neuritis" of the seventh nerve. Branching and misdirection of fibres have been shown histologically to be the basis of associated movements and "tics" after facial nerve section in the monkey (Howe *et al.*, 1937) and this process is well established as the pattern of re-innervation after nerve section in general (Young, 1942). The widespread distribution of the associated movements in many patients after facial paralysis indicates that severe disruption of the axone sheaths must have occurred. The end-result of facial paralysis shown in fig. 4 indicates that in this patient regenerating axones must have been able to enter axone sheaths going to all parts of the facial musculature.

Experimental studies in the rabbit have shown that complete recovery of function, as shown by the toe-spreading reflex, can occur after severe crushing of the peroneal nerve with watchmaker's forceps, but never after section and immediate suture (Gutmann, 1942). Gutmann and Young (1944) stated that, after crushing injuries, "the great majority of the fibres returning to the muscle after this operation are, therefore, in their appropriate channels" and Sanders and Whitteridge (1946) used crushing in their study of conduction velocity in regenerating nerve fibres because of "the absence of complicating factors—such as the shunting of fibres which invariably occurs after suture." The effects of compression of peripheral nerves have been studied histologically by Denny-Brown and Brenner (1944*a*, *b*). They showed that conduction

block was associated with histological changes in the axone cylinders and myelin sheaths. More prolonged trauma led to destruction of the axones but there are several references to the preservation of the Schwann cells and sheaths. These authors did not study the histological appearances in the stage of re-innervation but they stated that a 44-gramme spring clip applied to a nerve for several days led to a "preservation necrosis" of the axis cylinders and myelin sheaths.

It may be concluded, therefore, that compression of the facial nerve in the fallopian canal is not a satisfactory explanation of the end-results of facial paralysis seen in some patients. If the occurrence of complete necrosis of the compressed segment of nerve is postulated (Bauwens, 1950) then it is impossible to account for all the gradations of partial recovery and the varying degrees of associated movement. The fact that associated movements and blink-bursts occur in every patient after denervation implies that compression or ischæmia is not an adequate explanation of denervation in facial palsy. In addition the later development of crocodile tears after denervation shows that in 10 per cent, at least, of such patients the lesion must have been, to some extent, proximal to the geniculate ganglion. Surgical decompression is therefore fundamentally unsound and is doomed to failure. Even if it is argued that compression could produce conduction block without denervation, surgery would still be contra-indicated, because all patients without denervation recover completely within a few weeks.

The cause of Bell's palsy remains obscure. The severe disruption of the seventh nerve which evidently occurs suggests a severe and widespread lesion. It may well be that a parenchymatous neuritis, as suggested on pathological grounds over half a century ago by Minkowski (1892) and Dejerine and Theohari (1897) is the cause. The prognosis can now be established with accuracy but, at present, there is no evidence that any form of treatment has any influence on the outcome, which seems to depend entirely on the severity of the initial lesion.

Summary

The literature on Bell's palsy is briefly reviewed and some of the obscurities are discussed.

100 consecutive patients with Bell's palsy were studied clinically and electromyographically.

The patients were divided into 45 "successes" and 55 "failures" on the basis of the demonstration of fibrillation activity which indicates the presence of denervation. The 45 successes recovered completely in an average time of fifty-one days. The 55 failures have not recovered in

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periods up to three years. The degree of recovery of power and development of sequelæ are extremely variable and unrelated. Crocodile tears developed in 6 patients, contracture in 36 patients and associated movements in 55 patients.

Electromyographic analysis showed the presence, in all 55 failures, of blink-bursts consisting of grouped motor unit potentials synchronous with blinking. Associated movements and blink-bursts are shown to result from branching and misdirection of the regenerating axones.

These findings indicate that, in many patients, the lesion causing denervation is of such severity that it cannot be attributed to compression of the nerve in the fallopian canal.

It is concluded that surgical decompression of the facial nerve is not justifiable in the management of Bell's palsy.

ACKNOWLEDGMENTS

I am indebted to Mr. J. Hainsworth of the Department of Medical Photography, St. James's Hospital, Leeds, for fig. 1 and figs. 7–13 and to Mr. A. L. Pegg and Mrs. M. Clayson of the Department of Photography, University of Leeds, for figs. 2–6.

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*Uber die Auffassung einer Anomalien der Muskelinnervation.

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LEGENDS TO PLATES

PLATE XX

FIG. 2.—♀, 49 years. R. Bell's palsy of three years' duration. A, In repose. B, Looking up. C, Showing teeth. D, Closing eyes. Note varying pattern of dimpling of chin in B, C, and D. The pictures in figs. 2–6 were taken under identical photographic conditions.

PLATE XXI

FIG. 3.—♀, 52 years. L. Bell's palsy of two years' duration. ABCD as in fig. 2 in this and figs. 4–6. Note contracture and different patterns of dimpling of chin in B, C and D.

PLATE XXII

FIG. 4.—♂, 13 years. R. Bell's palsy of one year's duration. Partial recovery of voluntary movement, with associated movements but no contracture. Note different patterns of dimpling of chin in B, C and D.

PLATE XXIII

FIG. 5.—♂, 36 years. R. Bell's palsy of two years' duration. Good recovery of voluntary movement, with slight associated movements but no contracture.

PLATE XXIV

FIG. 6.—♀, 15 years. L. Bell's palsy of eight months' duration. Almost complete return of voluntary movements, with marked associated movements (D) but no contracture.

PLATE XXV

FIG. 12.—♂, 41 years. Two small scars of R. cheek of 30 years' duration. Full face in repose to show deepening of R. naso-labial fold and widening of the R. palpebral fissure.

PLATE XXVI

FIG. 13.— ♂, 41 years. (Same patient as fig. 12.) A, R. cheek at rest to show scars. B, R. cheek during blinking to show upward movement and deepening of scars. A and B taken under identical photographic conditions.

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FIG. 2.

To illustrate article by D. Taverner.

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PLATE XXI

FIG. 3.

To illustrate article by D. Taverner.

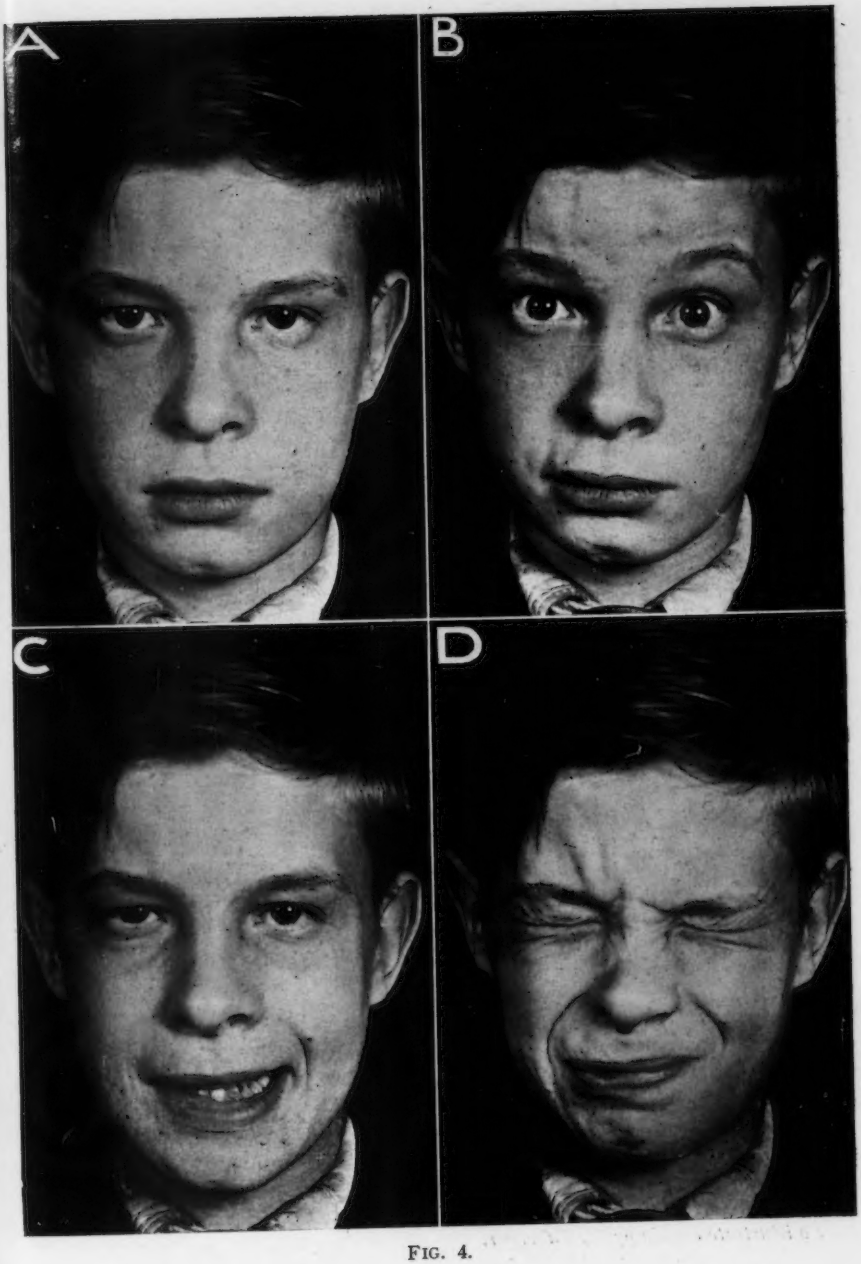

FIG. 4.

To illustrate article by D. Taverner.

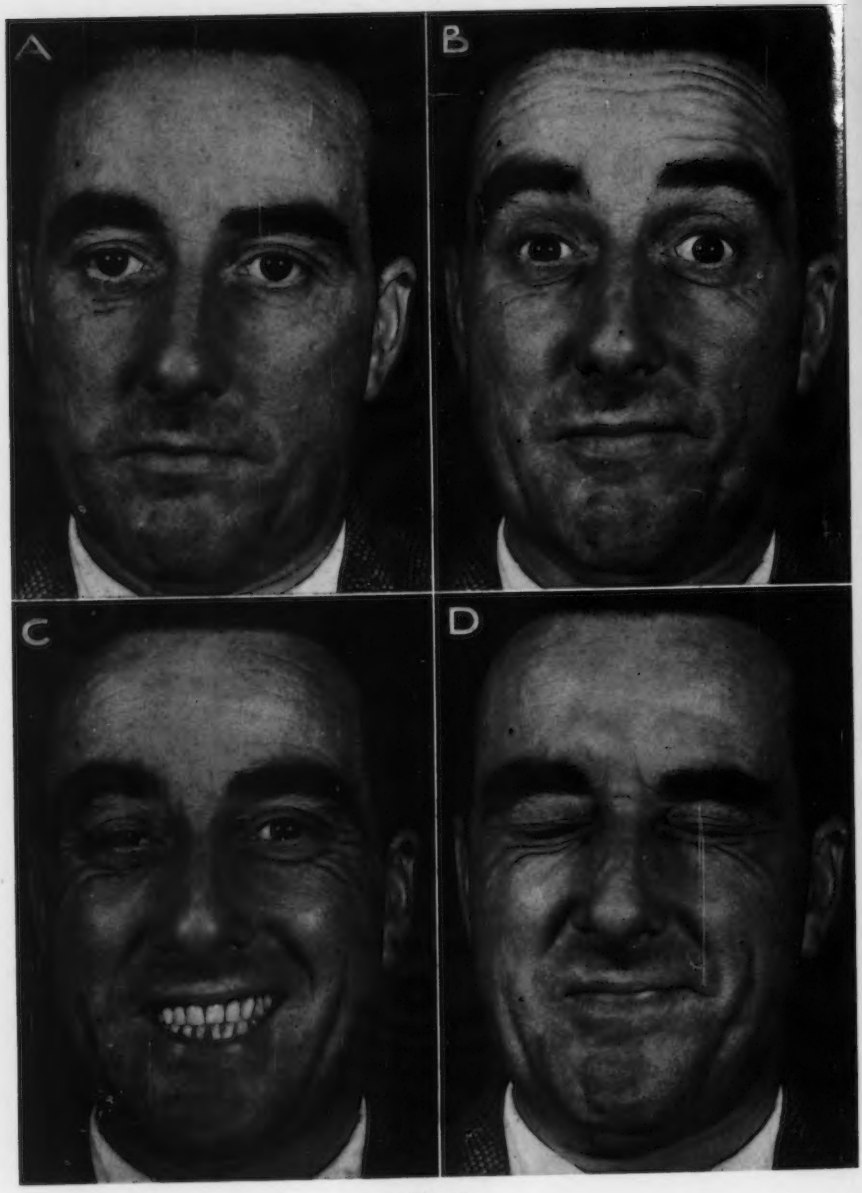

FIG. 5.

To illustrate article by D. Taverner.

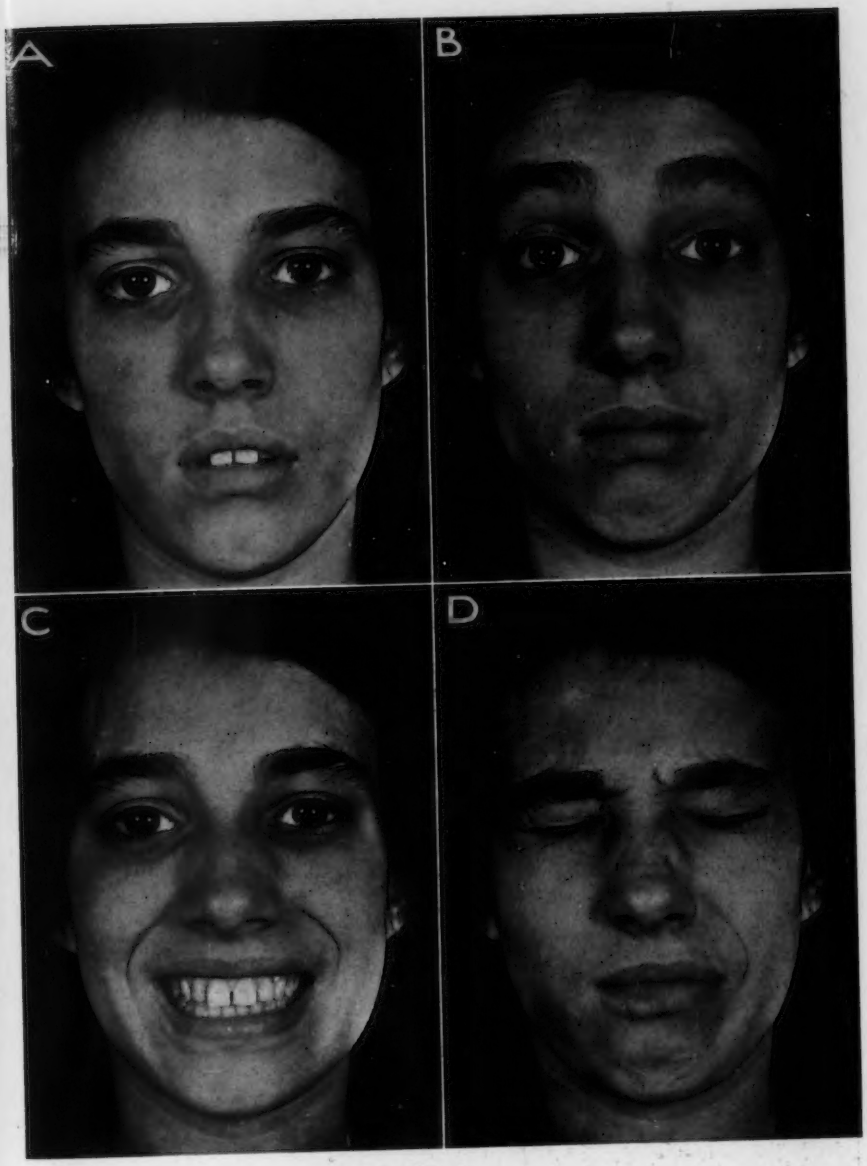

FIG. 6.

To illustrate article by D. Taverner.

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PLATE XXV

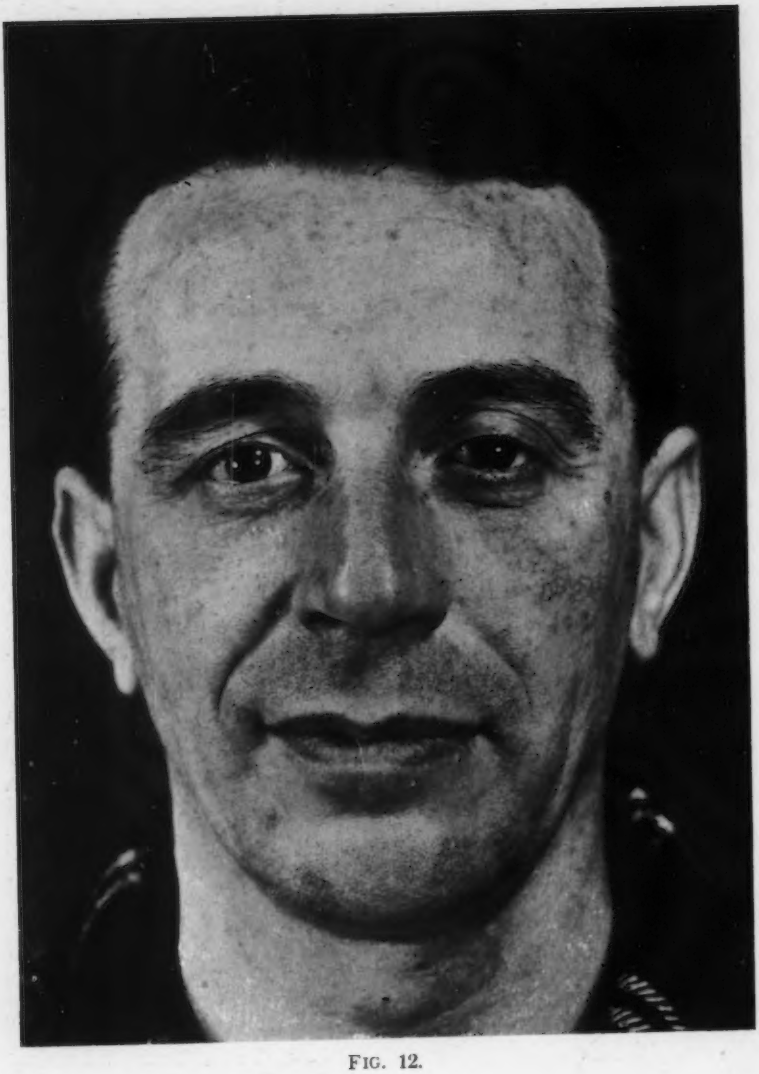

FIG. 12.

To illustrate article by D. Taverner.

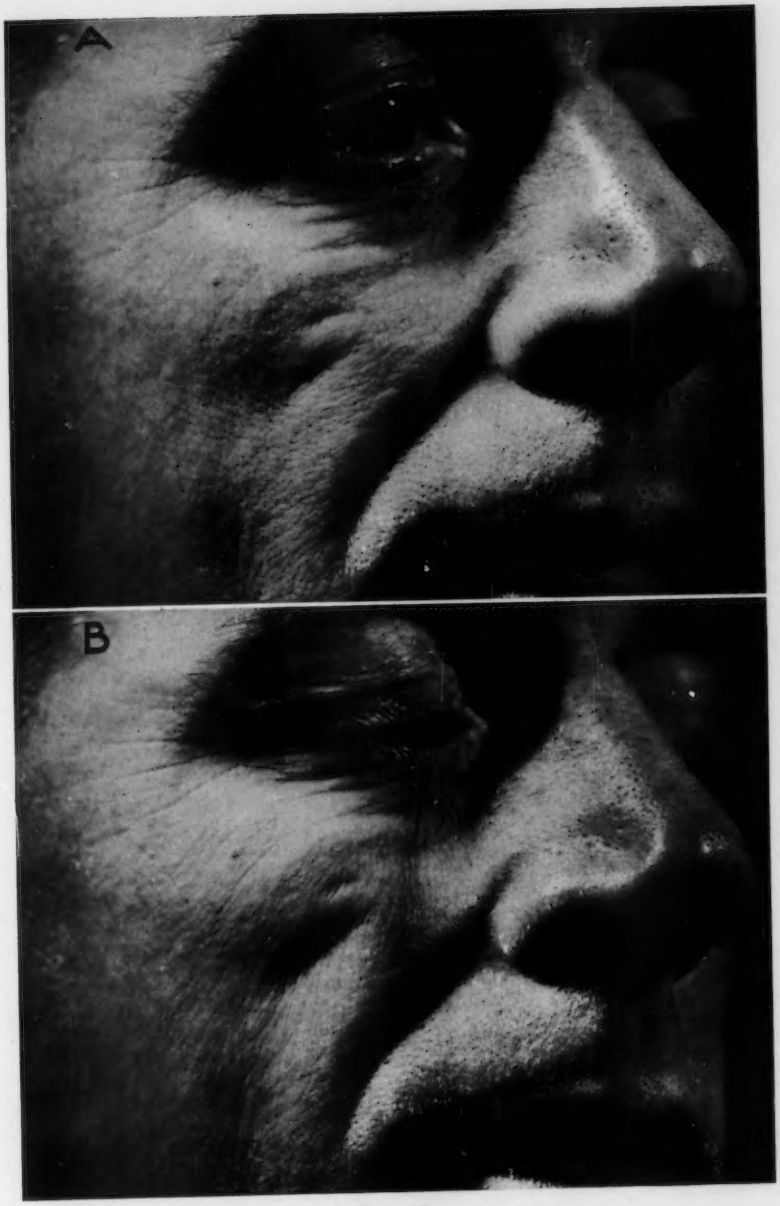

FIG. 13.

To illustrate article by D. Taverner.

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THE RADIOLOGICAL CRITERIA AND FAMILIAL OCCURRENCE OF PRIMARY BASILAR IMPRESSION

BY

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THE radiological diagnosis of basilar impression depends on the measurement of the relation of the upper parts of the cervical spine to the skull. The purpose of this paper is to compare three different measures, and to discuss the familial distribution of primary basilar impression and the light that this throws on the validity of the three criteria.

PREVIOUS INVESTIGATIONS

The first criterion is that of Chamberlain (1939), who stated that in normal subjects "all parts of the atlas and axis lie caudad of the base line" drawn from the dorsal margin of the hard palate to the dorsal lip of the foramen magnum (Plate XXVII). Saunders (1943) pointed out that there is a considerable range of variation in normal subjects, and found that in one person in three the tip of the odontoid lay above Chamberlain's line. McGregor (1948) introduced a modification of Chamberlain's line, namely "the line drawn from the upper surface of the posterior edge of the hard palate to the most caudal point of the occipital curve in the true lateral X-ray" (Plate XXVIII). He found that this line was easier to draw with precision than Chamberlain's line, and that the distance from it of the odontoid tip in normal subjects did not differ from the corresponding distance from Chamberlain's line by more than 3 mm. in any one case. Fischgold and Metzger (1952) measured the relation of the tip of the odontoid to a line joining the tips of the mastoid processes and to a line joining the digastric grooves. In the present investigation their method has not been used for two reasons: first that it differs essentially from those of Chamberlain and McGregor only in that the arbitrary base line is drawn on an antero-posterior view of the skull, and secondly that it frequently requires the use of tomography.

One of us (Bull, 1946, 1951) pointed out that in cases of basilar impression secondary to bone softening it is the weight-bearing parts of the occipital bone, namely the antero-lateral parts adjacent to the foramen magnum, which rise. Since the condylar portions of the atlas rise *pari passu* with the occipital condyles, it was suggested that the angle

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between the plane of the hard palate and the plane of the atlas vertebra would measure the degree of basilar impression (Plate XXIX). The plane of the atlas is obtained by drawing a line from the middle of the anterior arch of that vertebra to the middle of the posterior arch, as seen in a lateral radiograph. Although this angle might be expected to vary with the degree of flexion or extension of the neck, we have not found this to be the case. This possible factor has, however, been eliminated in the present investigation, since all radiographs were taken with the patient prone, the head in the true lateral position, and the chin in the neutral position, neither flexed nor extended. In this paper the angle as a criterion of basilar impression is compared with the measures of Chamberlain and McGregor, and their relative diagnostic validity is assessed.

The Present Investigation

Measurements in Normal Persons

Lateral radiographs of the radiologically normal skulls of 120 patients of the National Hospital were chosen for measurement, each decade between the ages of 10 and 69 years being represented by 10 males and 10 females. From each radiograph were determined the values[1] of Chamberlain's measurement c in mm. and McGregor's measurement m in mm. (that is, the perpendicular distances between the odontoid tip and the respective base lines), and the angle in degrees between the plane of the hard palate and the plane of the atlas vertebra, henceforth referred to as the angle β. The frequency distributions of the three measures are illustrated by the histograms in fig. 1; each approximates to a "normal" curve of distribution. (The measurements on the 120 normal subjects are analysed and compared with other published figures in Appendix I.)

Selection of Patients with Primary Basilar Impression

For the group of patients judged provisionally to have primary basilar impression there were chosen those patients of the National Hospital in whom a clinical or radiological diagnosis of primary basilar impression had been made and whose measurements (*see* Appendix II) for at least one of the three criteria were above the appropriate mean value for the 120 normal subjects by three or more times the corresponding standard deviation, namely $\beta = +13°$ or more, $c = +7$ mm. or more,

[1]It should be noted that Chamberlain's and McGregor's measurements have been taken as positive when the odontoid tip is *above* the respective base lines; all values, including those found by previous investigators, have been tabulated in accordance with this convention, which ensures that abnormality is associated with increasingly positive values of the measurements, as is also the case with the angle β.

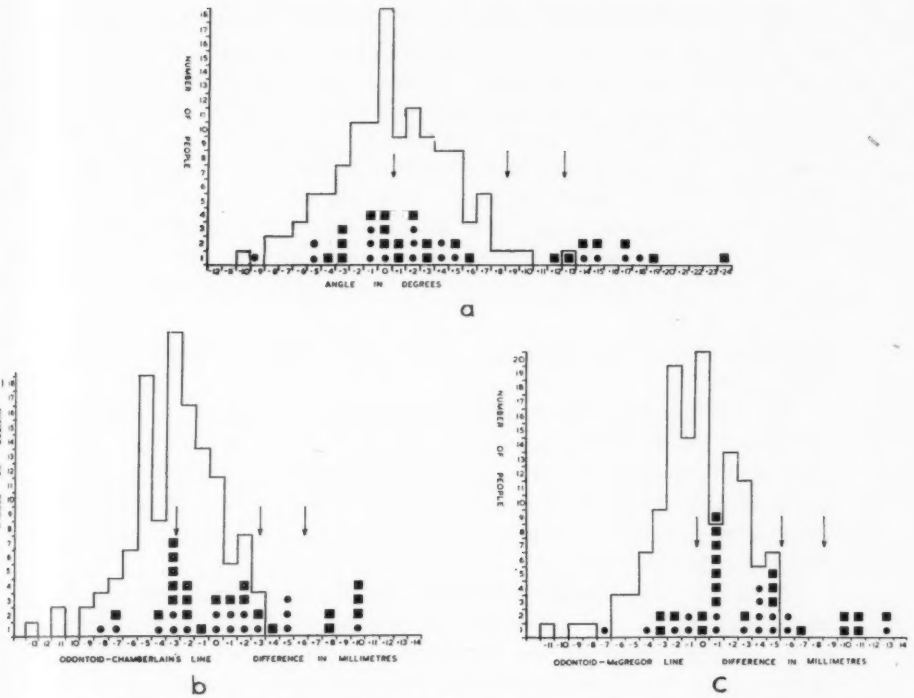

FIG. 1.—Frequency distributions of measurements on 120 normal radiographs for (*a*) the angle between the plane of the hard palate and the plane of the atlas vertebra; (*b*) Chamberlain's measure; (*c*) McGregor's measure.

● — each of 17 relatives of 9 patients with primary basilar impression by all three criteria

■ — each of 22 relatives of 11 patients with primary basilar impression by one or two of the three criteria

↓ ↓↓ — indicate (from left to right) the mean values of 120 normals, and twice and three times the standard deviation above the mean respectively.

and $m = +9$ mm. or more. 20 such patients were found : of these, 18 were abnormal according to the angle β (the 2 patients not so abnormal had nevertheless values of $+10°$ and $+11°$ respectively), 12 were abnormal according to the Chamberlain criterion, and 12 according to the MacGregor criterion. 9 patients were abnormal according to all three criteria, and 6 abnormal according to the angle β alone. (Two further patients were excluded from the present study, one with gross asymmetry of the foramen magnum, and the other with a congenital absence of the posterior arch of the atlas.)

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These 20 radiologically abnormal patients could be divided clinically into three groups: the first (10 patients) in which the radiological abnormality was an incidental finding not associated with any symptoms, the second (7 patients) in which a clinical diagnosis of syringomyelia had been made, and the third (3 patients) in which the neurological symptoms and signs could be explained by a local lesion at the level of the foramen magnum. Patients with basilar impression secondary to bone softening will be the subject of another communication. The 10 symptom-free patients were found in a series of about 30,000, giving a figure for general prevalence of the abnormality of at least 1 in 3,000.

Investigation of the Relatives of Patients with Primary Basilar Impression

All available relatives of the 20 radiologically abnormal patients were X-rayed. Of 39 relatives, 29 were radiologically normal and 10 were abnormal by at least one criterion (using the provisional criterion values given above). Of these 10, 6 were abnormal by all three criteria and the other 4 by the angle β alone; all 10 were symptom-free (for measurements *see* Appendix II).

Relatives of the 9 patients abnormal by all three criteria.—When the measurements for the 17 relatives of those 9 patients abnormal by all three criteria are considered, it will be seen (fig. 1) that the angle β differentiates these 17 persons more effectively into a group of normals and a group of abnormals, and also detects more abnormals, than either of the other two measures.

Relatives of all 20 abnormal patients.—The same pattern emerges with the addition of the measurements of the 22 relatives of the remaining 11 patients who were abnormal by only one or two of the three criteria (fig. 1): the angle β alone divides the 39 relatives into two clearly separate groups, of 28 normal and 11 abnormal persons respectively. The mean values and standard deviations of the angle β for these two groups are given in Table I; those for the 28 normal relatives will be seen to agree very well with the corresponding values for the 120 normal subjects.

Further statistical analysis.—As a further test, the values of the angle β for the whole material (120 normal subjects +20 abnormal patients +39 relatives=179 persons) were combined into a single frequency distribution; this was bimodal, with a high peak at an average value of about 0° for normals and a lower peak at about +16° representing an average abnormal value. This single distribution was analysed by a maximum likelihood method (*see* Rao, 1948, for details) into two

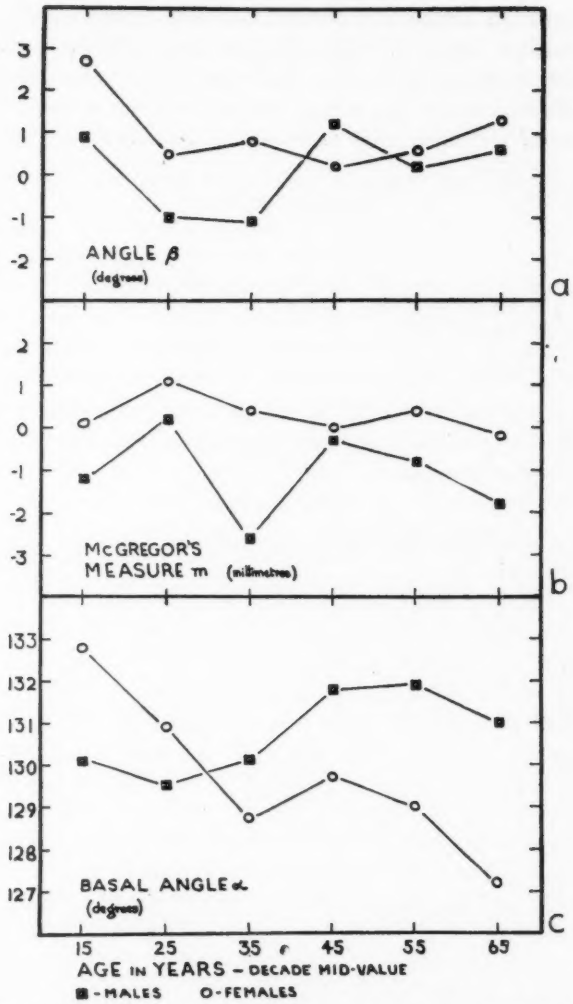

FIG. 2.—Relation between mean value and age, for males and females separately, for (*a*) the angle β in degrees; (*b*) McGregor's measure m in mm.; (*c*) the basal angle α in degrees (from Table X).

"normally" distributed components. This method does not assume *a priori* that a particular value of the angle β belongs to one or other of the two (overlapping) component distributions, but provides estimates of their mean values and standard deviations and of the proportion of mixture in the total material. The estimated proportion of mixture so

obtained was 152 normal : 27 abnormal, which compares very well with the proportion 148 : 31 derived from the arbitrary criterion of abnormality so far adopted. The estimates of the respective means and standard deviations are in good agreement with the values derived from the groups of 28 normal and 11 abnormal relatives (*see* Table I).

TABLE I.—MEANS AND STANDARD DEVIATIONS OF ANGLE β IN NORMAL AND ABNORMAL SUBJECTS

	Normals		*Abnormals*	
Source	*Mean*	*SD*	*Mean*	*SD*
Sample of 120 normal subjects	+0·58°	4·04°	—	—
Groups of 28 normal and 11 abnormal relatives	+0·14°	3·50°	+16·18°	3·37°
Total material (179)—estimates	+0·35°	3·73°	+16·16°	6·40°

It therefore appears that the angle β discriminates satisfactorily between a group of normals and a group of abnormals in respect of primary basilar impression.

DISCUSSION

It may seem that the foregoing analysis lies open to a charge of *petitio principii;* in rebuttal, the argument may be summarized as follows. Primary basilar impression is a skeletal malformation, involving the relation between the cervical spine and the base of the skull, which varies in degree in different persons and which occurs in persons both with and without neurological symptoms. Three measures on lateral skull radiographs have been proposed as diagnostic criteria : two (Chamberlain's and McGregor's) by previous investigators and the third (the angle β between the plane of the hard palate and the plane of the atlas vertebra) by one of the present authors (J. W. D. B.). The mean values and standard deviations of these three measures for the general population were estimated from a sample of 120 persons, and an arbitrary and provisional criterion of abnormality (namely, a value for at least one of the three measures which exceeds the estimated general mean by three or more times the corresponding standard deviation) was set up on statistical grounds. 20 patients of the hospital were found to satisfy this criterion, and their available relatives were similarly examined. The 39 relatives were found to fall into two clearly distinct groups *on the basis of the angle β alone,* 28 of them having values of β distributed more or less symmetrically about the estimated general mean with the same standard deviation, and the remaining 11 forming a separate group with a mean value of about +16° and a standard deviation of about 4°, the high positive value indicating the presence of the malformation. It is therefore concluded that there is a

real (genetically determined) skeletal malformation, detectable principally by means of the angle β and not nearly so well by the other two measures proposed, as distinct from a merely statistical abnormality. That the angle β is the best diagnostic criterion is supported by the fact that it played the principal role even in the provisional statistical definition of abnormality (it failed—but only just—to define 2 only of the 20 statistically abnormal patients, whereas Chamberlain's and McGregor's measures each failed in 8 cases, with values as low as +1 mm. and +3 mm. respectively).

The range of variability of the angle β both for normal and for abnormal persons is such that some degree of overlap is to be expected, however, so that a value falling within the region of overlap cannot be designated with confidence as either normal or abnormal. Hence a determinate value of the angle as a criterion of abnormality can be specified only on statistical grounds, and these in turn depend on estimates of the risks involved in misclassification. In a scientific study of the condition it would seem desirable, in view of its comparative rarity, to make sure that a group of alleged abnormals (which is not likely to be large) contains as few persons with high normal values as possible, even though some low abnormal values be consequently misclassified as normal: for this purpose the criterion value +13° or more for abnormality already used provisionally would seem to be suitable. In clinical practice, on the other hand, where the angle would be used as a diagnostic criterion, it would be safer to use a somewhat lower value: the maximum likelihood analysis already mentioned, taken with the observed range for the group of abnormal relatives, suggests +10° as a suitable value to raise a suspicion of primary basilar impression.

The mode of inheritance of primary basilar impression remains to be considered. This investigation was initially prompted[1] by the observation that the parents of one of the patients (Family A—*see* Appendices II and III) were first cousins; the familial distribution of the affected relatives in this family does not, however, suggest a recessive mode of inheritance, nor was there any additional instance of parental consanguinity in the other 17 patients of this series for whom the information was available. In one further case, encountered since the present investigation was completed, the parents were first cousins. Of the 20 abnormal patients in the present series, 7 were found to have one or more radiologically abnormal relatives (for details of measure-

[1]The only published record we have found of the familial occurrence of primary basilar impression is that of Scoville and Sherman (1951), who reported (without giving measurements) the occurrence of primary basilar impression with atlanto-occipital fusion in two sisters, one with an Arnold-Chiari malformation.

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ments, etc., *see* Appendix II; pedigree charts appear as Appendix III). Of these 7 patients, 4 were from the symptom-free group, 2 from the group with associated syringomyelia, and 1 from the group with symptoms due to local pressure. The ratio of abnormals to normals is similar in the sibs (3 : 10) and parents and children (7 : 19) of affected persons. There were two instances (Families J and L) where both parents of an abnormal patient were normal; in the other two instances (Families A and F) where both parents were available for examination, one parent was abnormal in each case. In the 7 cases where one parent only was available, 3 parents were normal (Families G, M, R) and 3 parents abnormal (Families K, Q, S) with one parent (Family C) doubtfully abnormal with a value of +12° for the angle; this value is, however, probably indicative of abnormality. Birth order was not found to be significant (*see* Table II, which follows the method of Turner and

TABLE II.—BIRTH-ORDER and SIBSHIP SIZE OF 27 AFFECTED PERSONS

Order of birth	*Size of sibship*												*Total*	*Expectation*
	1	2	3	4	5	6	7	8	9	10	11	12		
1	6	4	2	.	.	.	.	.	.	.	.	.	12	11·6
2		1	2	.	.	.	.	.	.	.	.	1	4	5·6
3			1	1	.	.	.	.	.	.	.	.	2	3·1
4				1	1	.	.	.	.	.	.	1	3	1·5
5					.	.	.	.	.	.	.	.	0	1·0
6						.	.	.	.	.	.	1	1	0·8
7							.	.	.	1	.	.	1	0·8
8								2	.	.	.	1	3	0·8
9	$\chi^2 = 0{\cdot}64$ with 2 DF								.	.	.	1	1	0·5
10	(non-significant)									.	.	.	0	0·5
11											.	.	0	0·4
12												.	0	0·4
Total	6	5	5	2	1	0	0	2	0	1	0	5	27	27·0

Penrose, 1931). Although there are too few patients to enable a firm conclusion to be drawn, the findings are compatible with the tentative hypothesis that the mode of inheritance is Mendelian dominance with an occasional failure of manifestation of the abnormal gene.

SUMMARY AND CONCLUSIONS

(1) A new radiological measurement, the angle between the plane of the hard palate and the plane of the atlas vertebra, is proposed as a diagnostic criterion for primary basilar impression, and its validity relative to certain criteria previously proposed, namely those of Chamberlain and McGregor, has been examined.

(2) On the basis of a provisional criterion of abnormality derived

from the observed distributions of the three measurements for 120 normal subjects, the radiographs of 20 patients were judged to indicate the presence of primary basilar impression.

(3) The radiographs of 39 available relatives of these 20 patients were obtained and examined; these relatives were found to fall into two distinct groups, of 28 normal and 11 abnormal persons respectively, when judged by values of the angle alone. Discrimination was not nearly so clear when the other two measures were used.

(4) It is concluded that primary basilar impression is a genetically determined skeletal abnormality which is best discriminated by means of the angle between the plane of the hard palate and the plane of the atlas vertebra.

ACKNOWLEDGMENTS

The physicians and surgeons of the staff of the National Hospital, Queen Square, allowed us to see the patients and their relatives. Dr. Eliot Slater, Director of the Genetics Unit, Institute of Psychiatry, gave us much advice and encouragement. Dr. E. A. Carmichael provided a financial grant from the Medical Research Council Neurological Research Unit for travelling expenses. Professor Sir Wilfrid Le Gros Clark advised us about the appropriate reference points for measurement of the basal angle. The following physicians and surgeons obtained for us radiographs of subjects who were unable to attend the National Hospital: Dr. W. Bain; Dr. O. H. Bostock; Dr. G. L. C. Colenso-Jones; Mr. J. S. Gibson; Dr. M. McAlley; Dr. G. A. MacDonald; Dr. E. A. Pryce; Dr. P. Watts. Mr. A. H. Prickett and the Department of Medical Photography, Institute of Neurology, were responsible for fig. 1, the pedigrees, and the reproductions.

To all of the above we wish to express our thanks.

APPENDIX I

STATISTICAL ANALYSIS OF DATA

Lateral radiographs of the radiologically normal skulls of 120 patients were chosen for measurement: on each X-ray were determined the values of Chamberlain's measurement c in mm., McGregor's measurement m in mm., and the angle β in degrees. Certain other measurements were made which failed to discriminate between normals and abnormals, and which are therefore not recorded: these comprised the length of the clivus, the relationship to the plane of the hard palate of the anterior and posterior margins of the foramen magnum, and the angle between the plane of the hard palate and the plane of the clivus. The basal angle α in degrees was also measured and is discussed in this appendix, partly because flattening of the basal angle (platybasia) was formerly confused with basilar impression, and also because this measurement was found to give a limited discrimination between certain of the groups studied. The three points taken for measuring the basal

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angle were (*a*) the nasion, (*b*) the "pituitary point," that is, the mid-point of the ridge named the tuberculum sellæ, and (*c*) the basion.

The means and estimated standard deviations of the four chosen measures for the 120 normal subjects were computed, and "normal" distributions based on these values fitted to the data. The goodness of fit was tested in each case by means of the appropriate value of χ^2, and the results, together with the probability P of as bad a fit or worse, are collected in Table III. The "normal" fit for the

TABLE III.—MEANS AND STANDARD DEVIATIONS OF 4 MEASUREMENTS ON 120 NORMAL RADIOGRAPHS, WITH χ^2-TEST OF GOODNESS OF FIT OF "NORMAL" DISTRIBUTIONS

Measurement	*c*	*m*	α	β
Mean	−2·86 mm.	−0·39 mm.	130·23°	+0·58°
SD	3·03 mm.	3·02 mm.	5·38°	4·04°
χ^2	10·26	8·06	10·67	5·05
DF	8	8	13	10
P	0·25	0·43	0·64	0·89

two angles is good; the slight skewness in the sample distributions (similar to that shown by McGregor's (1948) sample) of the linear measurements may indicate the presence of some degree of non-linear geometrical relationship between the lengths and the angles.

Table IV permits the comparison of the present material with previously published data. The differences in Table IV have been tested for statistical significance, with the results summarized in Table V. The two significant standard deviation differences only just attain significance at the 5 per cent level; the differences in mean values are much more serious, however, every one of them being significant. It is of interest to note that for the present sample the mean value of McGregor's measure *m* is greater (by 2·47 mm., with individual differences ranging from 0 to 5 mm.) than that of Chamberlain's measure *c*, a necessary consequence of the fact that McGregor's base line cannot lie above Chamberlain's on a single radiograph. When a similar comparison is made between the *different* samples, however, it will be seen that the mean values of *c*, both for Saunders' data and that of Poppell *et al.* (1953), are greater than McGregor's own mean for his measure, and that Poppell's value for the mean of *c* exceeds the mean of *m* for the present material as well.

A possible origin of some of the discrepancies may, however, be derived from the following considerations. McGregor (1948) stated that he found a slight sex-difference for his measure in his sample of Bantus, but for the purposes of his paper he felt able to ignore it. His figures, together with the corresponding ones for the present material, appear in Table VI. In each sample there is a similar mean sex-difference of the order of 1–1·5 mm., the female mean value being in each case the more positive; in both cases the difference is significant at the

TABLE IV.—MEANS AND STANDARD DEVIATIONS OF CHAMBERLAIN'S AND MCGREGOR'S MEASURES

Measure	*Source*	*Number in sample*	*Mean*	*SD*
Chamberlain's	Saunders (1943) ..	100	−0·94 mm.	3·6 mm.
	Poppell *et al.* (1953)	102	+0·06 mm.	3·3 mm.
	Present series ..	120	−2·86 mm.	3·0 mm.
McGregor's ..	McGregor (1948) ..	203	−1·32 mm.	2·62 mm.
	Present series ..	120	−0·39 mm.	3·02 mm.

TABLE V.—COMPARISONS OF CHAMBERLAIN'S AND MCGREGOR'S MEASURES, WITH TESTS OF SIGNIFICANCE

Comparison		*Diff.*	*Test*	*Significance*
Saunders *v.* Poppell	*c* SD	+0·3 mm.	$F = 1{\cdot}2$ (99, 101 DF)	Non-sig.
	Mean	−1·00 mm.	$t = 2{\cdot}04$ (200 DF)	Sig. at 5 per cent
Poppell *v.* Present series	*c* SD	+0·3 mm.	$F = 1{\cdot}2$ (101, 119 DF)	Non-sig.
	Mean	+2·92 mm.	$t^* = 6{\cdot}49$ (220 DF)	Very sig. (0·1 per cent)
Saunders *v.* Present series	*c* SD	+0·6 mm.	$F = 1{\cdot}4$ (99, 119 DF)	Sig. at 5 per cent
	Mean	+1·92 mm.	$t^* = 4{\cdot}17$ (63 DF)	Very sig. (0·1 per cent)
McGregor *v.* Present series	*m* SD	−0·40 mm.	$F = 1{\cdot}33$ (119, 202 DF)	Sig. at 5 per cent
	Mean	−0·93 mm.	$t^* = 2{\cdot}80$ (222 DF)	Sig. at 5 per cent

*Aspin-Welch modified *t*-test (*Biometrika* (1949), **36,** p. 290 ff.).

TABLE VI.—MCGREGOR'S MEASURE—SEX DIFFERENCES

Sample	*Sex*	*No.*	*Mean*	*SD*
McGregor (1948) ..	♂	164	−1·53 mm.	2·53 mm.
	♀	39	−0·44 mm.	2·80 mm.
Present series ..	♂	60	−1·08 mm.	3·19 mm.
	♀	60	+0·30 mm.	2·70 mm.

TABLE VII.—MCGREGOR'S MEASURE—SIGNIFICANCE OF SEX DIFFERENCES

Comparison		*Diff.*	*Test*	*Significance*
Males *v.* females McGregor	SD	−0·27 mm.	$F = 1{\cdot}23$ (38, 163 DF)	Non-sig.
	Mean	−1·09 mm.	$t = 2{\cdot}37$ (201 DF)	Sig. at 5 per cent
Males *v.* females Present series	SD	+0·49 mm.	$F = 1{\cdot}40$ (59, 59 DF)	Non-sig.
	Mean	−1·38 mm.	$t = 2{\cdot}57$ (118 DF)	Sig. at 5 per cent
McG. *v.* Present series Males	SD	−0·66 mm.	$F = 1{\cdot}59$ (59, 163 DF)	Sig. at 5 per cent
	Mean	−0·45 mm.	$t^* = 1{\cdot}00$ (88 DF)	Non-sig.
McG. *v.* Present series Females	SD	+0·10 mm.	$F = 1{\cdot}08$ (38, 59 DF)	Non-sig.
	Mean	−0·74 mm.	$t = 1{\cdot}31$ (97 DF)	Non-sig.

*Aspin-Welch modified *t*-test.

5 per cent level. When, however, the two groups of females are considered apart from the males, the difference between them is certainly not significant; neither is that between the two male groups (Table VII).

This similarity in two samples of such different character tends to confirm McGregor's suggested sex-difference for his measurement. Moreover, when males and females are considered separately, the significance of the difference between the two samples as a whole disappears, the significance attaching wholly to the sex-difference. In view of the close relationship between McGregor's measure and that of Chamberlain, a similar sex-difference is to be expected for the latter, and has in fact been found in the present sample, the relevant data being given in Table VIII. The Chamberlain sex-difference is almost exactly the same as that for McGregor's measure for the present material given in Table VI, and is similarly significant. It could not, however, account for the discrepancies between the present material and the data given by Saunders and by Poppell *et al.*, even if

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TABLE VIII.—CHAMBERLAIN'S MEASURE—MEANS AND SDs OF 60 MALES AND 60 FEMALES, WITH TESTS OF SIGNIFICANCE OF SEX DIFFERENCE

			Diff.	*Test*	*Significance*
SD	♂	3·16 mm.	+0·44 mm.	$F = 1{\cdot}12$ (59, 59 DF)	Non-sig.
	♀	2·72 mm.			
Mean	♂	−3·55 mm.	−1·38 mm.	$t = 2{\cdot}55$ (118 DF)	Sig. at 5 per cent
	♀	−2·17 mm.			

their samples were composed entirely of females. Saunders omits to state the sex-composition of his sample; that of Poppell *et al.* was "predominantly male."

It is also worthy of note that since McGregor's measure is on the average more positive by about 2·5 mm. than that of Chamberlain, the mean value of *m* for Saunders' sample will be about +1·5 mm., and that for Poppell's sample about +2·5 mm. (with a standard deviation of 3–4 mm. in each case): in either case, the odontoid tip must lie above McGregor's base line in noticeably more than half the cases considered (in the present material *m* is positive for 15 of the 60 males and 28 of the 60 females). In their paper, Poppell *et al.* seem to have considered McGregor's and Chamberlain's measures as effectively equivalent: they quote McGregor's mean value of *m* for his Bantu sample (viz. −1·32 mm.) in direct comparison with their own and Saunders' mean values of *c* (viz. +0·06 and −0·94 mm. respectively). In fact, however, the mean value of *c* for McGregor's Bantus must be about −3 mm. at best, and very possibly as low as −3·8 mm., which is quite irreconcilable with the values of Saunders and of Poppell *et al.*

In sum, therefore, there are in the case of Chamberlain's measure unexplained differences in mean value among the three available samples; but the discrepancy in McGregor's measure between the two available samples is entirely attributable to a significant sex-difference, females having on the average more positive values than males. The superior stability of McGregor's measure bears out his contention that his base line is better defined than that of Chamberlain.

In view of the foregoing observations, the angle β and the basal angle α were also examined for sex-difference, with the results given in Table IX. It is of

TABLE IX.—ANGLE β AND BASAL ANGLE α—MEANS AND SDs OF 60 MALES AND 60 FEMALES SEPARATELY WITH TESTS OF SIGNIFICANCE OF SEX DIFFERENCES

Angle				*Diff.*	*Test*	*Significance*
β	SD	♂	4·14°	+0·22°	$F = 1{\cdot}12$ (59, 59 DF)	Non-sig.
		♀	3·92°			
	Mean	♂	+0·13°	−0·89°	$t = 1{\cdot}20$ (118 DF)	Non-sig.
		♀	+1·02°			
α	SD	♂	5·32°	−0·04°	—	Non-sig.
		♀	5·36°			
	Mean	♂	130·73°	+1·01°	$t = 1{\cdot}04$ (118 DF)	Non-sig.
		♀	129·72°			

interest to note that the sex-difference for the angle β is in the same sense as that for the linear measures—females have the higher average value—but only a very much larger sample could give any idea of its significance.

As the sample of 120 normal subjects was stratified by age as well as by sex, there being 10 persons of each sex in each decade between the ages of 10 and 69, it was possible to examine the data for any trend with age. The means and standard deviations for McGregor's measure, the angle β and the basal angle α are collected in Table X. Each set of standard deviations was tested for heterogeneity by means of Bartlett's test: those for the basal angle for either sex, and for the other two measures for females, were not significantly heterogeneous. For males,

TABLE X.—MEANS AND SDs OF β (DEG.), m (MM.), AND α (DEG.) FOR 10 MALES AND 10 FEMALES IN EACH DECADE FROM 10+ TO 60+ YEARS

	Decade		10+	20+	30+	40+	50+	60+
β	♂	Mean	+0·9	−1·0	−1·1	+1·2	+0·2	+0·6
		SD	7·1	2·8	3·8	4·3	3·7	2·0
	♀	Mean	+2·7	+0·5	+0·8	+0·2	+0·6	+1·3
		SD	4·3	4·8	4·5	2·9	3·8	3·4
m	♂	Mean	−1·2	+0·2	−2·6	−0·3	−0·8	−1·8
		SD	2·3	4·4	4·1	2·6	1·6	3·3
	♀	Mean	+0·1	+1·1	+0·4	0·0	+0·4	−0·2
		SD	3·8	3·2	2·3	2·1	2·5	2·3
α	♂	Mean	130·1	129·5	130·1	131·8	131·9	131·0
		SD	4·2	5·7	4·5	4·3	7·1	6·5
	♀	Mean	132·8	130·9	128·7	129·7	129·0	127·2
		SD	5·1	5·2	3·9	5·4	5·1	7·0

however, the heterogeneity of variance for McGregor's measure almost attains significance at the 5 per cent level (Bartlett's $\chi^2 = 10{\cdot}89$ with 5 DF), and for the angle β is beyond the 1 per cent level (Bartlett's $\chi^2 = 15{\cdot}88$ with 5 DF). In the latter case the significance appears to attach chiefly to the 10+ age group (SD=7·1°) and to a lesser extent to the 60+ age group (SD=2·0°). Interpretations of high values of the angle β in children and adolescents as indicative of abnormality should therefore be made with caution. As regards trends with age, the standard deviation both of McGregor's measure and of the angle β appears to decrease slightly with increasing age, whereas that of the basal angle appears to increase.

Considering now the regressions of the mean values on age, no very definite trends emerge (fig. 2). It will be seen that the sex-difference for McGregor's measure is present within each age group, whereas that for the angle β (non-significant) appears only in the first three age groups. In these first age groups the mean of the angle β at first falls and then rises slightly for both males and females, whereas the reverse occurs with mean m. Further investigation of larger samples may reveal that these tendencies are general, but there is no serious objection to the use of either McGregor's measure or the angle β for diagnostic purposes without taking account of age, at any rate for adults.

The relationship between the various measures in the present material was also examined. There was clearly so great a correlation between Chamberlain's and McGregor's measures, the maximum difference between them in the 120 normal subjects being 5 mm. with a mean of 2·5 mm. (for both males and females) over a range for each measure of about 17 mm., that in further comparisons Chamberlain's measure, as being the less well-defined observationally of the two, was not considered. Surprisingly enough in view of the fact that both are proposed as criteria for the same abnormality, the correlation between McGregor's measure and the angle β turns out to be very low ($r = +0{\cdot}25$ with 95 per cent confidence limits +0·07 and +0·41). Incidentally McGregor's own observation that there is no significant relationship between his measure and the basal angle α is confirmed by the present material ($r = +0{\cdot}13$, which is not significantly different from zero). Elimination of the age variable between the three measures taken in pairs reveals no obvious structural relationship between their mean values.

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TABLE XI.—MEANS AND SDs OF β, m AND c FOR SYRINGOMYELIA PATIENTS, 26 WITHOUT AND 11 WITH ASSOCIATED BASILAR IMPRESSION

Syringomyelia patients		β	m	c
Without basilar impression (26 patients)	Mean	+1·42°	+1·15 mm.	−1·54 mm.
	SD	4·97°	2·22 mm.	2·34 mm.
With basilar impression (11 patients)	Mean	+17·27°	+10·73 mm.	+8·00 mm.
	SD	4·86°	4·27 mm.	4·39 mm.

TABLE XII.—MEANS (WITH SDs) OF THE BASAL ANGLE α AND THE ANGLE β, FOR VARIOUS SAMPLES

Group	α	β
120 normal subjects..	130·23° (5·4)	+0·58° (4·0)
27* unaffected relatives	128·22° (8·0)	+0·50° (3·1)
9* affected relatives (symptom-free)	127·78° (6·4)	*+16·00°* (3·7)
10 patients with basilar impression (symptom-free)	130·00° (6·6)	*+17·80°* (5·0)
26 syringomyelia patients without basilar impression	131·00° (5·8)	+1·42° (5·0)
11 syringomyelia patients with basilar impression	*139·36°* (6·9)	*+17·27°* (4·9)
3 patients with basilar impression and pressure symptoms (values)	134°, *144°*, *180°*	*+26°*, *+41°*, *+35°*

*Certain basal angle values not available.

In view of the frequency of associated syringomyelia in our abnormal patients (7 cases in 20), and of the finding of McRae (1953) that 38 per cent of patients with syringomyelia had bony abnormalities in the region of the foramen magnum, the radiographs of 37 patients diagnosed as suffering from syringomyelia were examined. It was found that 11 of these (including the 7 already mentioned in the main part of this paper)—that is, 30 per cent—also had basilar impression (7 by all three provisional criteria, 3 by the angle β alone, and 1 by m and c but not by β, the value of the latter in this case being nevertheless +11°). Mean values of m, c and the angle β, with standard deviations, for the two groups of syringomyelia patients are given in Table XI. For the 26 syringomyelia patients without basilar impression, the mean values are very slightly but not significantly higher than those for the 120 normal subjects, whereas for the 11 with basilar impression the mean values are considerably higher, the mean of β being raised relatively more than the other two means.

It was also observed that the mean basal angle α for the 11 patients with *both* syringomyelia *and* basilar impression is also considerably raised, being 8·36° above the mean basal angle for the 26 patients *with* syringomyelia but *without* basilar impression (the difference is very significant as $t=3{\cdot}80$ with 35 DF, $P < 0{\cdot}1$ per cent), whereas the latter is within 1° of the mean basal angle for the 120 normal subjects. Reference to Table XII, in which figures for the various available groups have been collected, shows that it is the presence or absence of basilar impression which determines the average value of the angle β, whereas the presence of both syringomyelia and basilar impression is required for a raised mean basal angle. The basal angle values for the three patients with basilar impression and associated local pressure symptoms are also above the normal mean, two of them considerably so.

APPENDIX II

Data on 20 Radiologically Abnormal Patients and Their Available Relatives

Family	National Hospital Ref. No. of abnormal patient	Pedigree Ref. No. of family member (v. App. III)	Age at x-ray	Sex	Clinical group of patient (with hospital diagnosis)	Values of radiological measurements: Angle β (deg.)	Chamberlain's c (mm.)	McGregor's m (mm.)	Basal angle (deg.) α	Sib-order of abnormal person (where known)
A		II.2	71	♀		+14	+10	+13	127	2/12
		II.6	67	♀		+17	+10	+11	?	6/12
		II.8	61	♀		+19	+ 8	+10	132	8/12
		II.9	59	♀		+15	+ 8	+10	131	9/12
		II.14	60	♂		− 3	+ 2	+ 3	141	
	43931.....	III.1	24	♂ ...	Symptom-free (Wilson's disease)	+10	+ 5	+10	133	1/1
B	44757.....	I.1	76	♀ ...	Symptom-free (Facial palsy)	+23	+ 2	+ 3	124	1/1
		II.5	47	♀		0	− 2	+ 1	120	
		II.7	40	♀		+13	+ 4	+ 5	124	7/10
		II.9	36	♀		+ 2	− 2	+ 1	141	
		II.10	36	♀		− 4	− 3	+ 1	130	
C		I.1	52	♀		+12	0	+ 1	127	
	42590.....	II.3	13	♂ ...	Symptom-free (Epilepsy)	+11	+ 8	+10	137	8/8
D	29600.....		53	♀ ...	Symptom-free (Endogenous depression)	+15	+ 7	+ 7	128	4/4
E	16968.....	I.2	42	♀ ...	Symptom-free (Hypertension)	+22	+ 8	+11	144	4/5
		I.3	42	♀		+ 4	+ 1	+ 1	133	
		II.1	19	♀		+17	+ 5	+ 6	130	1/3
		II.3	10	♀		*	*	*	*	
F		I.2	68	♀		+ 1	+ 3	+ 7	112	
		I.3	65	♀		+24	+10	+11	120	8/8
		I.4	70	♂		+ 3	− 2	+ 1	120	
		II.1	42	♂		+ 5	+ 2	+ 5	139	
		II.2	38	♂		+ 6	− 1	0	131	
	20380.....	II.3	33	♂ ...	Symptom-free (Epilepsy)	+15	+ 4	+ 7	128	3/3
G		I.1	51	♀		+ 1	− 3	+ 1	129	
	22402.....	II.1	14	♂ ...	Symptom-free (Infantile hemiplegia)	+18	+ 3	+ 4	129	1/1
H	38725.....		67	♂ ...	Symptom-free (Cerebral arteriosclerosis)	+22	+ 3	+ 9	130	
I	33728.....		51	♂ ...	Symptom-free (Migraine)	+24	+ 1	+ 6	125	

[see over]

APPENDIX II—*continued*

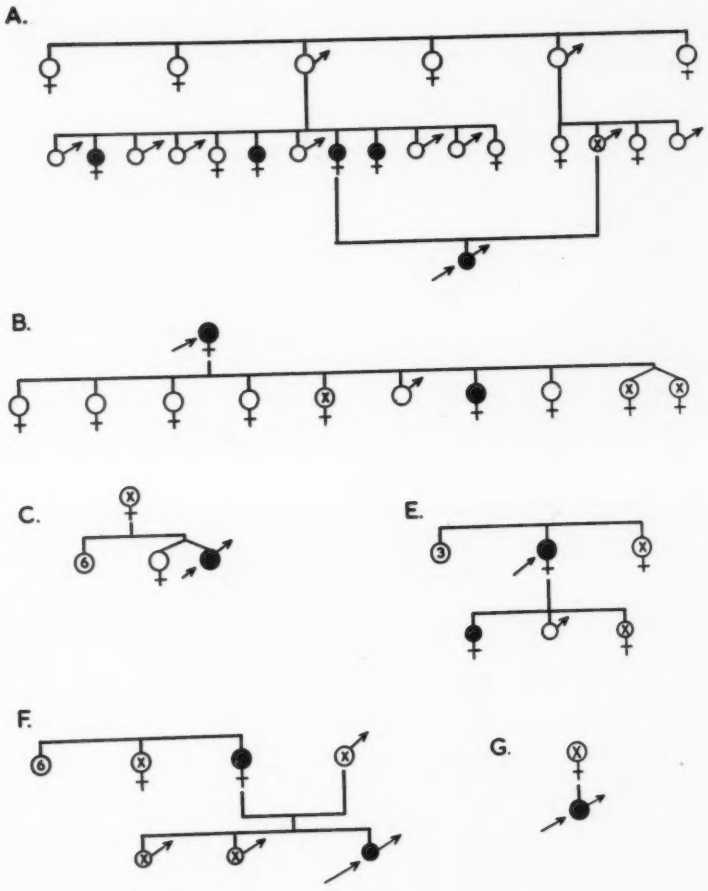
J		I.1	65	♂		− 3	− 7	− 2	122	
		I.2	59	♀		+ 3	+ 1	+ 5	120	
	43134.....	II.1	31	♂...	Symptom-free (Disseminated sclerosis)	+18	+ 8	+ 8	122	1/2
		II.2	27	♀		0	− 3	+ 1	121	
K		I.2	65	♂		+18	+ 2	+ 4	134	2/3
		I.3	61	♂♀		− 1	− 4	− 1	134	
	16532.....	II.1	33	♀...	Pressure	+41	+17	+17	144	1/2
		II.2	28	♀		− 1	− 3	+ 1	114	
L		I.1	42	♂		+ 4	+ 5	+ 5	130	
		I.2	40	♀		− 5	− 2	− 2	140	
	32625.....	II.1	9	♂...	Pressure	+35	+10	+16	180	1/2
		II.2	9	♀		*	*	*	*	
M		I.2	62	♀		− 1	− 3	− 3	131	
		II.1	39	♂♀		0	− 4	− 3	128	
	4249.....	II.2	35	♀...	Pressure	+26	+ 6	+ 7	134	2/3
N	22174.....	I.2	58	♂...	Syringomyelia	+13	+10	+14	155	2/2
		II.1	31	♀		0	+ 2	+ 4	130	
		III.1	12	♂		+ 2	0	+ 3	127	
		III.2	5	♂♀		*	*	*	*	
		III.3	1	♂		*	*	*	*	
O	6754.....		43	♂...	Syringomyelia	+22	+ 8	+12	143	1/1
P	16776.....	I.1	57	♂...	Syringomyelia	+23	+14	+17	130	1/3
		II.2	27	♂		+ 2	+ 1	+ 4	120	
Q	46277.....	I.1	56	♀		+15	+10	+13	137	
		II.1	37	♂...	Syringomyelia	+23	+11	+11	142	1/2
		II.2	35	♂♀		+ 5	+ 3	+ 4	134	
		III.1	4	♀		*	*	*	*	
		III.2	6	♀		*	*	*	*	
R		I.2	64	♀		− 3	− 3	0	137	
	29954.....	II.1	29	♀...	Syringomyelia	+19	+ 4	+ 5	135	1/1
	[Patient is V.2 in Family 293, *Treasury of Human Inheritance*, vol. 4, part 3 (Bell, J., and Carmichael, E. A., Cambridge, 1939)]									
S		I.2	73	♀		+14	+ 5	+ 6	118	4/12
		I.4	65	♂		+ 2	0	+ 5	128	
		I.6	76	♂		− 1	− 8	− 7	121	
	4062.....	II.1	42	♂...	Syringomyelia	+23	+ 8	+10	133	1/1
T	16234.....	I.1	50	♂...	Syringomyelia	+13	+10	+13	144	3/4
		II.1	20	♀		− 5	− 3	− 1	129	
		II.2	14	♂		− 9	− 7	− 4	?	

*The difficulty of defining the hard palate did not allow measurement of these patients.
Basal angle values were not obtainable for two persons, as their radiographs did not include the nasion.

APPENDIX III

● Abnormal by at least one criterion.

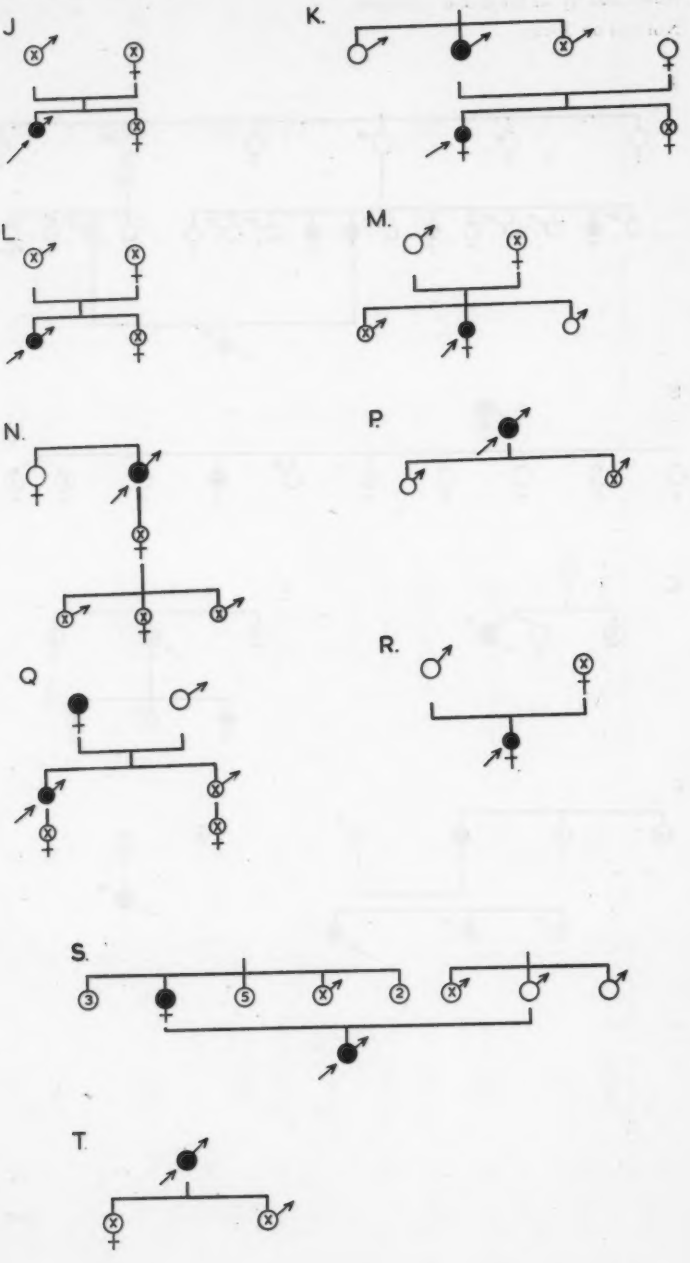
× Normal on X-ray.

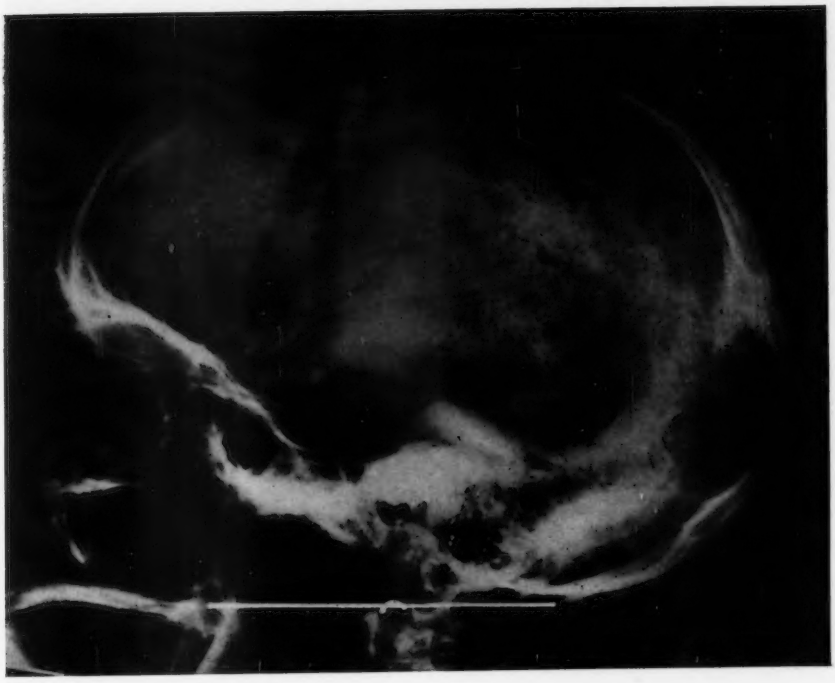


*The difficulty of defining the hard palate did not allow measurement of these patients.
Basal angle values were not obtainable for two persons, as their radiographs did not include the nasion.

[see over]

APPENDIX III—*continued*





To illustrate article by J. W. D. Bull, W. L. B. Nixon and R. T. C. Pratt.

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LEGENDS TO PLATES

PLATE XXVII

Radiograph showing Chamberlain's line and tip of odontoid process (*a*) in normal skull; (*b*) in primary basilar impression.

PLATE XXVIII

Radiograph showing McGregor's line and tip of odontoid process (*a*) in normal skull; (*b*) in primary basilar impression.

PLATE XXIX

Radiograph showing plane of the hard palate and plane of the atlas vertebra (*a*) in normal skull; (*b*) in primary basilar impression.

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LONG DESCENDING TRACTS IN MAN

I. Review of Present Knowledge

BY

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THIS review is a summary of what is known about the anatomy of the long descending tracts in man; the tracts are those that descend into the spinal cord, having originated in the brain above the medulla spinalis. Anatomical knowledge about these tracts in man is considered in detail; where evidence concerning human anatomy is deficient or unconfirmed, observations from other species will also be considered.

In this review, where our knowledge rests on the evidence of only one investigator or one piece of work or on one case, this will be referred to, but it will not be included in the summary of the section; in the final Table this evidence will be regarded as forming incomplete or unverified knowledge. As one of the aims of the review is to reveal the gaps in knowledge of the anatomy of the descending tracts, those parts of this anatomy that are well proved and well known in man, as, for example, the course of the cortico-spinal tract, will be mentioned only *en passant*.

When one traces the history of the acquirement of knowledge of the central nervous system, one notes that the first observations were made on human pathological material, and to a lesser extent on human embryos. To add to this picture, workers undertook experimental and embryological investigations on laboratory animals. It was implied that these investigations should serve as models to guide later investigations on man. But, as will be seen from this review, these later investigations have rarely been carried out. Instead, it has tacitly been assumed that the findings from laboratory animals are fully applicable to man; and there the work has stopped. Yet, as neurologists, pathologists, physiologists and anatomists, all of us are concerned with man. It is clear that one cannot assume that tracts are the same in man as in other species. It is obvious that a species with grasping pentadactyl hands is likely to have a different development of tracts in the central nervous system from an animal such as the dog, which uses its forelimbs merely for such stereotyped movements as those required for

running, swimming or digging. Even within the sub-order of Anthropoidea, it would clearly be unjustified to assume that tracts are the same for monkeys which proceed by brachiation or monkeys with prehensile tails which can be used for grasping food, as they are for man. And one notes that man's nearest relations, the gorilla, the chimpanzee, the orang-utan, and the gibbon, have been used most rarely in the investigation of the nervous system.

Many textbooks of the anatomy and physiology of the nervous system give a wrong impression of what is known. They contain dogmatic statements about the anatomy of tracts, and do not state what species they are discussing; they tend, however, to give the reader the impression that their statements apply to man. In every case it should be stated in what species the work was done. It may be that the anatomy of any or every tract is the same in man as in the rat or the cat, but this needs to be proved.

The order in which the tracts will be considered will be as follows:

1. Cortico-spinal tract.
2. Median longitudinal bundle.
3. Tecto-spinal tract.
4. Rubro-spinal tract.
5. Reticulo-spinal tract.
6. Vestibulo-spinal tract.
7. Olivo-spinal tract.

[8. Central tegmental tract.]
[9. Periaqueductal tract.]
[10. Hypothalamo-spinal tract.]

This order is based on those tracts having their cells of origin most cranially being considered first. The three tracts at the end are placed in brackets for the following reasons: in the case of the central tegmental tract, it is possible but not yet known whether it descends into the cord or not; in the case of the periaqueductal tract, it is not yet known whether it is an ascending, descending or mixed tract; in the case of the hypothalmo-spinal tract, it is unknown whether it exists in man, as it has so far been described only in the cat.

Terminology

There is no universally accepted nomenclature for the structures and tracts of the central nervous system. This lack of uniform terminology will be changed—it is hoped—by the International Congress of Anatomists which will be held in Paris in July 1955.

A nomenclature based on function was introduced into the anatomy of the nervous system when Broca re-named the pars opercularis of the inferior frontal gyrus the circonvolution du langage. The subsequent history of the relation of this gyrus to language stands as an example of the defects of a functional terminology in anatomy. A term, such as "motor cortex" may have some meaning to the physiologist or clinical

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neurologist (though it certainly means different things to many of them), but it is unsuitable to anatomy; the anatomist need not anchor his terminology to the drifting raft of function. It is also obvious that if a term like "motor cortex" is undesirable, then a bastard such as "premotor cortex" is such that no excuse can be made for its existence. In recent years the inadequacy of this kind of terminology has been made very clear when it was shown that the greater part of the "rhinencephalon" has nothing whatever to do with smell.

In general, the terminology in this review will be based on giving the name of the beginning and the end of the tract, as, for instance, tecto-spinal tract. Synonyms will be given at the outset, to aid workers familiar with other terminologies. The term "dorsal" will be used as the opposite of the term "ventral" and not as a synonym for "thoracic"; this was recommended in the B.N.A. in 1895, but it has not always been carried out. The terminology used is based on the upright posture, and not on that used by zoologists; the reason is that this usage is the common one with those working on man. Thus the terms "anterior" and "posterior" will be used, even in reference to quadrupeds, to mean "ventral" and "dorsal," and not to mean "cranial" and "caudal." Terms such as "direct" and "indirect" will be avoided, as they are unclear; but it is considered that the terms "crossed" and "uncrossed," "contralateral" and "ipsilateral" are free from ambiguity. It might be held that "crossed" and "uncrossed" are unnecessary; but in English they are useful in avoiding such dysphonious terms as "contralateral lateral cortico-spinal tract." With regard to the terminology of areas of the cortex, we have used the terminology of the authors quoted; thus the use of Brodmann's scheme of labelling the cortex does not imply that this or any other scheme of architectonic parcellation is considered especially desirable.

Cortico-spinal Tract

The cortico-spinal tract may be considered in three parts: the crossed lateral cortico-spinal tract, the uncrossed lateral cortico-spinal tract, and the ventral or anterior cortico-spinal tract. The uncrossed lateral division of the tract varies in size from being a few isolated fibres, to a compact, well-limited tract.

The pyramids of the brain were described by Willis in 1664, and their decussation was first adequately described by Petit in 1710. Charles Bell (1830) traced the fibres of the pyramid upwards "through the pons Varolii; then forming the anterior part of the crus cerebri (anterior to the corpus nigrum); and finally into the cerebrum." He did not

realize that the descending fibres, after they have decussated, cross to the lateral columns. The first man who understood this, and who adequately traced the fibres of the tract was Türck (1851). He described two tracts—the Pyramiden-Seitenstrangbahn (pyramid lateral column tract) and the Hülsen-Vorderstrangbahn (Hülse means a shell, husk, or outer covering, and so this might be rendered into English as the covering tract of the anterior column). He did not realize that there was any connexion between these two tracts. He traced these tracts in human pathological material by examining sections of the unfixed, unstained cord and brain. He concludes that the lateral tract was centrifugal, and that it conveyed "motor impulses." He traced the pyramid lateral column tract down to the last sacral nerves, and he noted that the ventral tract often extends less far caudally than this lateral tract. He did not find the cells of origin of the tracts, but he concluded that lesions of the following structures do not cause degeneration in the lateral tract: the caudate nucleus, the lentiform nucleus, the external capsule, the corpus striatum, and the superior colliculus. He found that small lesions of the internal capsule may cause degeneration of the tract, as do large lesions involving the corona radiata. He suggested that when large lesions of the lentiform nucleus do cause degeneration of the tract, that is because they then involve the internal capsule. He showed that the ventral tract is uncrossed; he believed that this tract originates in the lentiform nucleus.

Charcot named the ventral tract the "faisceau de Türck." Flechsig considered this undesirable. It has since that time become more so, as the name of Türck's bundle has been given to the temporo-pontine tract. In 1892, when there was much discussion of anatomical nomenclature before the Basle Committee did its excellent work, His wrote that the name "pyramidal tract" was undesirable, as it might be taken to indicate that the fibres of the tract originate in the pyramidal cells of the cortex. As will be seen in this review, this error has occurred. It is desirable that the name "cortico-spinal tract" should displace "pyramidal tract"; for a terminology giving the location of the origin and termination of a tract is advantageous. (Such a terminology—it is true—has the disadvantage that it may need revision as new knowledge accrues.) A further advantage of dropping the term "pyramidal tract" would be that the even more ambiguous term "extra-pyramidal" would also have to go.

After Türck, the main features of the anatomy of the tract were worked out by Bouchard, Charcot, and Flechsig. Bouchard (1866) realized that the two tracts described by Türck were the two divisions of

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one tract; he named them the faisceau encéphalique direct ou interne and the faisceau encéphalique croisé ou externe. Flechsig (1876) from his myelogenetic studies made the same discovery ten years later.

Schäfer (1883) discovered the uncrossed lateral cortico-spinal tract in the macaque. Sherrington also observed it in the dog, in 1885. Pitres (1884) first found this tract in man, reporting its occurrence in all 10 of 10 cases examined, in which there had been a unilateral cerebral lesion.

Cells of Origin

Man.—The cells of origin of the tract were not looked for by Türck. Flechsig introduced the method of observing the onset of myelination in embryos and babies, which he called myelogenesis. Before the definite establishment of the fact that small areas of the cortex subserve different functions by the electrical stimulation experiments of Fritsch and Hitzig, neurologists did not localize lesions with the precision to which we are accustomed.

It was mainly Charcot who taught us that lesions could be made to furnish evidence on the anatomy and function of the nervous system if their extent in three dimensions was carefully noted. And so Charcot, Pitres, and Flechsig, using this method of the charting of pathological lesions, and Flechsig, using the method of myelogenesis, confirmed each other's work in establishing the origin of the tract.

When Flechsig published his Leitungsbahnen in 1876, he had come to no conclusion regarding the origin of the tract; he had, however, observed that in two brains in which there was no cerebrum, there was no pyramidal tract, and indeed, no pyramids. In the same year Charcot reported that he found that destructive lesions of the cortical region, stimulation of which most easily produced movements, always cause degeneration in the spinal cord, whereas destructive lesions of other cortical areas do not do so. He showed that where there is degeneration in the lateral columns of the cord, there is not always a lesion involving the lentiform or the caudate nucleus. This was confirmed by Pitres (1876). Flechsig in the following year wrote that he had reached the same conclusions, from his observation of pathological material. He found that partial lesions of the cortical motor area cause partial degeneration in the cortico-spinal tract, and total degeneration of the cortical motor area is accompanied by total degeneration of the tract. Further work on myelogenesis, published in 1877, also showed that the tract has no connexion with the lentiform or caudate nuclei, and that it arises "chiefly in the region of the central gyri."

Two discoveries coming within a short time became associated to-

gether in the minds of the neurologists of that time. The first was one of the most important events in the history of neurology : the discovery of the electrical excitability of the cortex by Fritsch and Hitzig (1870); the second was the description by Betz in 1874 of the cells that now bear his name. The way in which these two new facts became linked together may be observed from the following quotation of Charcot and Pitres (1877). Discussing the importance of the fact that only certain regions of the cerebral cortex are electrically excitable, they wrote : "The histological researches of Monsieur Betz gave them a sort of indirect anatomical confirmation, in that they showed that the largest pyramidal cells (giant cells) are situated in the neighbourhood of the fissure of Rolando and in the paracentral lobule . . ." It soon became accepted that the electrical stimulation of what Ferrier (1876) called "the motor centre" easily caused movements because this stimulation excited the cells of origin of the cortico-spinal tract. And as these regions contained the Betz cells, it was accepted that these cells formed "the exact origin" of the cortico-spinal tract.

It was pointed out by von Monakow in 1915 that the Betz cells could not be the only or even the main source of the tract, for a large part of the tract originates in the area, stimulation of which gives movements of the upper limb, and as some of it originates in the area, stimulation of which gives movements of the face and larynx; and yet the former area contains very few and the latter area contains no Betz cells. As soon as counts were carried out on the Betz cells and the fibres of the tract, it was apparent that the assumption that the Betz cells were the only cells of origin of the tract was wrong.

The main features of the origin of this tract were known by 1905, when Flechsig wrote : "Far and away the greater part of the pyramidal tract comes from the precentral gyrus. The tract degenerates when lesions involve the middle and upper thirds of this gyrus and the paracentral lobule. When a lesion affects the lower third the number of degenerate pyramidal fibres is so small that usually a distinct area of degeneration cannot be found in the pyramids." After this had been definitely established, it remained to find out if all the cells of origin were located in the precentral gyrus and the paracentral lobule.

The only addition to knowledge has been made by Minckler, Klemme, and Minckler in 1944. They excised the cortex of area 6 of the frontal lobe bilaterally in a patient suffering from Parkinsonism. They confirmed by histological examination of the excised part that it had indeed come from area 6. They were able to trace the relevant degenerating axons into the cortico-spinal tract.

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Verhaart (1948) concluded that fibres of the fronto-pontine tract (Arnold's bundle) pass laterally to join the cortico-spinal tract somewhere between the peduncle and the lower pons. Dejerine (1901) had also believed this. But recent work, which included silver staining, by Meyer, Beck and McLardy (1947) and by Beck (1950, 1953) has shown no evidence that Arnold's bundle ("Fibres originating from granular frontal cortex, excluding area 8") "sends any appreciable number of fibres into the cortico-spinal tract."

Other species.—The evidence concerning the cells of origin of this tract is more complete for the monkey than it is for man.

At the close of the nineteenth century all those interested in this subject believed that in the monkey the cells of origin of the tract occupied the pre- and post-central gyri, and most workers believed that they extended on to the three frontal gyri and the frontal operculum.

It is interesting to see that Mellus (1894), for instance, wishing to trace the fibres of the "thumb focus" in the bonnet monkey (*Macacus sinicus*), made his lesion "at a point just above the lower end of the intra-parietal sulcus, and between it and the fissure of Rolando, and consequently just behind the inferior genus of the fissure of Rolando." In fact, one notes that he chose a small area of the post-central gyrus. The choice was correct, for he obtained degenerated cortico-spinal fibres running down as far as the thoracic segments in both lateral columns of the cord.

In 1915 von Monakow showed that in the dog and cat, the gyrus sigmoideus—which is the pre-central and post-central gyrus combined—gives rise to two-thirds of the fibres of the tract in the medulla oblongata. He found that all the fibres of the tract in the decussation degenerate when the whole hemisphere is removed.

However, Leyton and Sherrington (1917) found in anthropoid apes that lesions restricted to the post-central gyrus do not cause degeneration in the cortico-spinal tract.

All the following workers studied the macaque. Minkowski, von Monakow's successor, took up this problem and published the results of his careful and detailed study in 1923 and 1924. He showed that the cortico-spinal fibres arise not only in the precentral gyrus, but also in the post-central gyrus, and in that part of the frontal lobe which lies immediately anterior to the pre-central gyrus. He traced all these fibres into the lumbar segments. Hoff (1935) found that the tract arises from area 6 as well as from area 4. Kennard (1935) in her first publication on this subject stated that she found the fibres originating in area 6 could be traced into the second sacral segment; she found them mingled

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with those from area 4 "throughout the pyramidal pathways." Both Hoff and Kennard found the fibres from area 6 running contra- and ipsilaterally in the lateral tract. It is necessary to point out that Kennard's paper is somewhat misleading; for apparently she imagines that the pyramidal tract is thus named, as it originates in large pyramidal cells; its name of course derives from the pyramids of the medulla. Thus when Kennard writes of "non-pyramidal cortico-spinal fibres," she is not referring to cortico-spinal fibres which do not run in the pyramid, but to fibres which do not originate in the large pyramidal cells of area 4. The results reported by Kennard and Hoff were criticized by Levin (1936); he stated that "extirpation *en bloc* of the premotor area was performed up to the border of area 4. Injury to the neighbouring motor cortex, producing partial degeneration of the pyramidal tract, would under such circumstances appear almost inevitable." Levin and Bradford (1938) performed similar work, but they were unable to confirm Hoff and Kennard's findings that fibres originating in area 6 run in the cortico-spinal tract. In 1940, Kennard repeated these experiments with Verhaart; they then found only a few degenerate fibres in the tract following ablation or thermocoagulation of area 6. The discrepancy between the different findings of the two studies was accounted for, either on the belief that the lesions in the second study were too small to cause any but a few fibres "to be recognized as degenerated in the tracts," or the belief that "the lesions made in the first series being deep enough to injure tracts from areas other than area 6."

In 1937 Uesugi confirmed Minkowski's work, by showing that fibres from the post-central gyrus run into the cortico-spinal tract; most of them run contralaterally, but some are ipsilateral. Levin and Bradford (1938) also concluded from their studies on the macaque that "the bulk of the fibres of this tract arise in area 4 of Brodmann, but an appreciable portion (almost 20 per cent) arises in areas 3, 1, 2 and 5 of the parietal lobe." They also found that "the anterior portion of area 4, a zone 1–2 mm. wide, does not send fibres to the spinal cord"; but they added the reservation that this area could give rise to fibres reaching the cord above the fourth cervical segment; for that was the level of their hemisection. Peele (1942) confirmed their work by showing that fibres from areas 3, 1, 2, 5 and 7 enter the tract. In 1944 he reported further work, which showed that the fibres arising in the parietal lobe run into both crossed and uncrossed lateral tracts.

There is ample evidence in the macaque and the mangabey that no region rostral to Brodmann's area 6 sends fibres into the cortico-spinal tract. This was established by Kennard (1935) and Mettler (1935, 1947).

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However, Verhaart (1948) concluded from a study of two gibbons that some small fibres running with the fronto-pontine tract leave this tract in the pons and continue caudally with the cortico-spinal tract.

Lassek (1942) found that in the macaque extirpation of area 4 causes degeneration of about a third of the fibres of the tract just rostral to the decussation, and that these are the largest fibres. He also found that few if any fibres originate in the parietal lobe. In a later paper (1952) he wrote that a third of the fibres in the pyramid remain after ablation of the entire frontal lobe; these are all fine fibres. He could not find out where they originated; they do not take origin in the parietal lobe or the basal ganglia; it seems from his study that they must arise in the temporal or occipital lobes. For Levin and Bradford (1938), Mettler (1944) and Lassek (1952) showed that all the fibres coursing through the pyramids are of cortical origin. Mettler (1944) removed area 4 and found that this caused degeneration of all the myelinated fibres of the tract in the macaque, leaving the unmyelinated fibres intact. As he pointed out: "If myelin stains of the classic type are used, no intact fibres can be seen in the pyramids." In considering the origin of these fibres, he came to the conclusion that they were "definitely of cortical origin."

In the dog, Morin, Poursines and Maffre (1951) showed that 67 per cent of the fibres originate in an area corresponding to area 4 in man, 20 per cent arise posterior to this in the posterior segment of the sigmoid gyrus, and 9 per cent anterior to this. As these workers used Weigert preparations, their conclusions refer only to myelinated fibres.

In 1953, Walberg and Brodal showed that in the cat some fibres of this tract originate in the temporal and occipital lobes. This has never been noted before, and requires confirmation.

A physiological method of finding the cells of origin in the cat, rabbit, dog and monkey was introduced by Woolsey and Chang in 1948. They stimulated the pyramid electrically and recorded the potential changes from the cortex. In the monkey, they found that the parietal cortex makes a large contribution to the tract, the main contribution of this lobe coming from the rostral portion of the post-central gyrus. In the cat and the rabbit, they picked up action potentials in the "anterior ectosylvian gyrus." In the cat, Marchi preparations "showed numerous heavy and fine degenerations in the ipsilateral pyramid" after ablation of the "second" somatic area; this degeneration was "followed through the decussation into the upper cervical levels of the lateral cortico-spinal tract." In summarizing their findings in the monkey, they state: "The region of cortex in which the antidromic potentials

were found to occur in the monkey consists grossly of areas 8, 6, 4, 3, 1, 2, 5 and 7 of Brodmann. The occurrence of potentials in areas 8 and 6 may be explained, perhaps, by cortico-bulbar fibres in the pyramids."

Summary.—In man, most of the cells of origin of the cortico-spinal tract are situated in the precentral gyrus, mainly in its upper two-thirds, and in the paracentral lobule. In the monkey, in addition to the regions just mentioned in man, it is known that cells of origin are situated also in the parietal lobe, that is the post-central gyrus, including areas 3, 1, 2, 5 and 7, and also in area 6 of the frontal lobe.

Course

Man.—The main facts concerning the course of the tract will not be given here, as they have passed into the corpus of well-established knowledge.

Ugolotti in 1900 found evidence that some fibres arise in the cortical cells of one hemisphere, cross in "some interhemisphere commissure," and then descend in the opposite cortico-spinal tract. He found such fibres in 18 of 20 cases of degeneration in the tract. These fibres were found to descend into the sacral region. Later workers never mention such fibres in man.

At the beginning of the century it was also often believed that there was a crossing in the cord of some of the fibres of the crossed lateral cortico-spinal tract back to their side of origin. Modern workers have found no evidence to support a belief in the existence of recrossed tracts.

The relations of the cortico-spinal tract are well known and shown in all textbooks. Within the internal capsule, Dejerine (1901) showed on the basis of 37 cases that the cortico-spinal tract lies anterior to the temporo-pontine tract. In more recent years, Pfeifer (1934) and Meyer, Beck, and McLardy (1947) showed that it lies posterior to the fronto-pontine tract.

Other species.—In the cat, Walberg and Brodal (1953) claim that some of the fibres of this tract, including those from the "motor area" and those from the temporal and occipital lobes, which they described, cross in the corpus callosum and descend through the contralateral internal capsule and cerebral peduncle to the contralateral pyramid. Thus in this species there are fibres from one hemisphere running in both lateral and both ventral cortico-spinal tracts. Some fibres from each hemisphere do not cross in the pyramidal decussation, some cross from their side of origin to the opposite side of the cord, and some cross in the decussation to return to their side of origin, having been on the

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opposite hemisphere which they had reached via the corpus callosum. The majority of fibres crossed the decussation from the side of their origin to the opposite side of the cord. It will be remembered that Ugolotti claimed that the same pattern is to be found in man.

Variations and Abnormalities

Man.—The early workers noted that this tract is subject to much anatomical variation. This variation from individual to individual is likely to be associated with the fact that this tract is a phylogenetic newcomer. A phylogenetically old tract, such as the median longitudinal bundle, is not subject, it seems, to variation from subject to subject. Further such an ancient tract keeps the same position in the brain and cord of all species. But a phylogenetically new tract like the corticospinal tract shows great variation in its position in various species. In rodents it runs in the posterior columns, in the mole in the anterior columns, and in carnivores and the rabbit in the lateral column. It may well be that as it develops late ontogenetically, it sometimes finds its anlage already occupied.

Flechsig in his original work (1876) on this tract devoted much space to the variations which he found. His description of the corticospinal tract as consisting of two lateral and two ventral tracts was accompanied by the statement that this was only the commonest pattern. He found that the variations occur mostly in the region of the decussation. He found one pyramidal tract following the commonest pattern and the other crossing completely, so that there were two lateral tracts and one ventral in 6 cases (10 per cent). He found total crossing of the tract, leaving no ventral tract in 3 cases (11 per cent). Although he never found a case without the decussation, the whole of the tract descending as the ventral tract, he mentioned in a footnote that such a variation very probably occurs. This abnormality was first reported by Kramer (1949), and again by Verhaart and Kramer (1952); in one case of Kramer's this was the only abnormality, but in their other specimens, there were also other abnormalities, the commonest of which was an encephalocœle. Weil and Lassek (1929) found a total crossing of the tract, there being no ventral tract, in 2 of 10 cases examined.

Lesser deviations from the usual pattern are common; they are, as was found by Flechsig, usually related to the decussation. A common group of variants is for some of the fibres to cross the mid-line abnormally cranially. Fibres may decussate in the upper pons. Hoche (1898) first described this kind of abnormality; in his case fibres crossed the mid-line at the level of the facial nucleus; they became scattered in

the medial lemniscus; lower in the medulla oblongata they took up a more lateral position; after the main decussation, they formed the medial part of the lateral cortico-spinal tract. The same abnormality was described by Mme Dejerine (1900) who called these aberrant fibres "fibres aberrantes de la voie pédonculaire." She said that the whole cortico-spinal tract sometimes took this course. Verhaart (1953) says that some fibres take this course in the medial lemniscus in all human brains. Occasionally a bundle of the fibres lies dorsal to the lemniscus.

In another group of variants, fibres leave the main bundle some distance cranial to the decussation, and remain on the same side as they descend the cord. Barnes (1901) described a bundle leaving the main mass of the tract, immediately cranial or caudal to the decussation, descending ipsilaterally on the surface of the medulla oblongata and the cord in the antero-lateral column. This bunch of fibres may leave the rest of the tract, lying posterior and lateral to the olive; it then keeps this same lateral position, being joined caudal to the decussation by the rest of the lateral cortico-spinal tract. These fibres do not always form a discrete bundle; in Barnes' second case it was spread out parallel to the surface of the cord between the median fissure and the denticulate ligament; a few fibres continued dorsally from here, so that there were some cortico-spinal fibres between the lateral crossed and the ventral uncrossed tracts. He stated that his ventro-lateral tract is about a quarter of the size of the normal ventral tract. Barnes reported it in 5 cases. It was also reported by Risien Russell (1898), Mme Dejerine (1900), who called it "fibres pyramidales homolatérales superficielles," and by Spiller (1902).

Pick described a well-known variation (1890). In his case a small bunch of fibres left the main mass cranial to the decussation and ran postero-laterally into the ipsilateral restiform body. He looked for this bundle in 100 other brains, but could not find it. Schaffer (1890) described a similar bundle to that of Pick; but in his case the bundle was within the grey matter, just lateral to the nucleus cuneatus. He thought that this bundle was not a part of the cortico-spinal tract, but consisted of a bundle of posterior column fibres, passing into the restiform body. It is possible that Pick's bundle was similar. Barnes (1901) found a similar bundle to that of Pick, and thought that it ran to the nucleus ambiguus. Mme Dejerine (1900) thought this bundle descends into the cord. Ugolotti (1902) found Pick's bundle in 3 of 26 brains examined; in none of them could he trace it below the medulla oblongata. Lewandowsky (1904) reported a case in which there were two abnormal bundles; they both left the main tract caudal to the decussation

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and turned round to run orally in a reversed direction. He considered that this was a similar course to that of Pick's bundle. Karplus and Spitzer (1904) reported a case in which a bundle separated from the tract at the caudal end of the pons and split into several smaller bundles; one lay within the root of the fifth nerve, and one apparently disappeared into the reticular substance.

Another typical abnormality in the medulla oblongata is for the external arcuate fibres to cut across the pyramidal field, cutting the tract into bundles.

Obersteiner (1902), from his great experience, concluded that "Variations in the course and the position appear in no other tract as commonly and of such an extent as in the pyramidal tract." It might be pointed out, however, that owing to the size and the interest of this tract abnormalities and variations become conspicuous. Further, as so little is known about other tracts in man, it is unlikely that there has been enough material examined to give us information on the occurrence of variations on the normal.

In 1895, von Monakow reported a case in which one cortico-spinal tract had degenerated in infancy and in which the other tract showed compensatory hypertrophy. Dejerine (1901) in "Anatomie des Centres Nerveux" reported a similar case, that of Rivaud. Later, in 1902, the Dejerines again reported this case; they stated that there was "considerable hypertrophy of the bulbar pyramid of the healthy side, which is almost of double volume"; this case showed also a very large uncrossed lateral cortico-spinal tract, coming from the healthy hemisphere; it formed a compact bundle. Marie and Guillain (1903) reported a similar case; in their case, there was no hypertrophy of the ipsilateral lateral tract, but the contralateral ventral tract was hypertrophied. A similar case was reported by Catola (1904). Oeconomakis (1905) reported a case in which the region of the origin of the cortico-spinal tract had been replaced by microgyria; this obviously must have occurred *in utero,* and so, in this case, it was possible that the hypertrophy of the remaining tract had started before birth. A further case of hypertrophy of the remaining normal pyramid was reported by van der Bruggen (1930). Verhaart (1950) investigated this hypertrophy in two cases in which "hypertrophy of one pyramid might be expected, as in each, the other pyramid had been almost totally destroyed in early youth." Both van der Bruggen and Verhaart counted the fibres in their cases. Verhaart found that there was no increase in the number of thin fibres, but that there was an increase in the number of larger fibres. There was also hypertrophy of the fronto- and the temporo-pontine

tracts. He believed that in the cortico-spinal tract this compensatory increase in thick fibres occurred after birth and that it resulted from the thickening "of an abnormally large number of thin fibres." For, although there were more fibres than usual measuring more than 3 μ, the number of fibres below 3 μ was well within normal limits. It is true that also in the normal, thick fibres develop after birth. It seems that some such explanation as Verhaart's is likely; for one is unwilling to believe that new cortical neurones come into being after birth.

Termination: Relation to Grey Matter

Man.—It is not yet generally accepted that the fibres of this tract end around the zona intermedia at the base of the posterior horn; most of the evidence, however, indicates this. It used to be held that the fibres run to the motor horn cells of the ventral horn, but there was never adequate evidence supporting this belief.

Flechsig (1876) found that the fibres of the lateral tract stream into the grey substance in the region between the anterior and posterior horns, and that they then run towards the anterior commissure. He could not trace them farther than this; he thought it unlikely that they cross in the commissure, as the fibres which he traced running towards the commissure were fine ones, and the fibres that make up the commissure are large. He found that the fibres of the tract do not turn into the grey matter in bundles, but "usually singly or in little groups of a few fibres"; this is also so in the cervical and lumbar enlargements. Von Monakow (1895) came to the same conclusion from his pathological material. He considered that the tract runs into the grey matter in the region between the anterior and posterior horns, and that between the termination of these fibres and the anterior horn cells there was a "Schaltneurone." Lewandowsky (1904) found the same termination in one case.

The evidence of the mode of termination of the ventral tract points to the fact that each tract supplies the anterior horns of both sides. This was shown by Hoche (1898), Risien Russell (1898), the Dejerines (1904) and Frey (1913). What proportion of the axons crosses the mid-line near their termination remains completely unknown. The opinion of Cajal (1909), that the axons remain ipsilateral, seems to have been based on deduction from clinical findings, and not from anatomical facts.

Other species.—Von Monakow (1886), using von Gudden's method, excised the relevant cortex, in the newborn kitten, and looked for the changes in the spinal grey matter six months after the injury. He could

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find no changes in the anterior columns of the grey matter, but he found much degeneration "in the processus reticularis of the grey matter (that is to say in the angle between the anterior and posterior horn)" of the contralateral side. He concluded that it was unlikely that the cortico-spinal fibres end directly on the anterior horn cells. Schäfer (1899), who worked on the monkey, found the fibres passing towards Clarke's column and to the base of the posterior horn. Simpson (1902) made "motor cortical lesions" in cats, dogs, and monkeys; he found the degenerate cortico-spinal fibres ending "in the grey matter at the base of the posterior horn in the cervical and lumbar enlargements." Lewandowsky (1903) also concluded from Marchi studies of dogs and apes that the fibres of the ipsilateral and contralateral cortico-spinal tract end in the zona intermedia. Rothmann (1903) criticized Lewandowsky's work, pointing out that the problem could not be solved by the Marchi technique; for considering that myelinated fibres lose their myelin sheaths somewhere near their termini, he denied that the point where the Marchi granules ceased was the point where the axon terminated. In 1907 Simpson and Jolly made both partial and complete excisions of the whole of the pre-central gyrus in calithrix and *Macacus rhesus*. They showed clear drawings of the fibres of the lateral tract entering the grey matter at the base of the posterior horn. This was so at all levels down to and including the fifth lumbar segment. In 1934, Hoff and Hoff showed that in the macaque, baboon and chimpanzee, the axons terminate in the zona intermedia, and that in the chimpanzee some of them end in the ventral horn near the motor cells. Hoff (1935) later showed that in the macaque, the parts of the tract originating in area 4 and in area 6 go to the grey matter of both sides of the cord. Although the Hoff's method of demonstrating boutons by means of Cajal's reduced silver technique has been severely criticized by Schimert (1938) and by Barnard (1940), the conclusions to which they came would seem to be correct. Szentagothai-Schimert (1941) investigated the termination of this and other tracts in the cat, using Reumont's method and the Bielschowsky and Bielschowsky-Gros techniques. In 15 cats he never found degeneration near the anterior horn cells; he found that the fibres go to the cells of the intermediate zone and the ventral part of the posterior horn. Walberg and Brodal (1953) traced the component of the tract that arises in the temporal and occipital lobes, in the cat, to the dorsal horn, as well as to the zona intermedia.

Leyton and Sherrington (1917) found that in the anthropoid apes there is a ventral tract, as in man; they found that it runs to the contralateral anterior horns.

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Termination: Caudal Extent

Man.—It is known that the crossed lateral part of the tract continues into the conus medullaris. It was shown by Dejerine and Thomas (1896) and by Risien Russell (1898) that the uncrossed lateral part continues into the last sacral segments.

The caudal extent of the ventral tract varies greatly from subject to subject, and even in one subject on the two sides of the cord. Dejerine and Thomas (1896) and Dejerine in many of his writings report cases showing this division of the tract extending down into the last segments of the cord. Risien Russell (1898) and Lewandowsky (1905) also report similar cases. Frey (1913) found that the tract only rarely descended into the sacral region; and Nicolesco and Hornet (1933) in 14 cases never once found it descending caudal to the upper thoracic region. In some cases it does not extend below the cervical region. Flechsig (1876) first propounded the theory that the total number of cortico-spinal fibres is constant, and that the size of the lateral and the ventral tracts are inversely proportional one to the other. This idea is generally accepted. But after examining drawings of transverse sections from many cases in the literature, we do not believe that it is generally true. Obvious cases where the contrary is true are the Dejerines' case Bigot (1904) and the case reported by Risien Russell (1898); in these cases there is a great deal of degeneration in the ipsilateral and the contralateral tracts, as well as much degeneration in the ventral tract, which extends in Russell's case as far caudally as the third sacral segment.

The aberrant bundle described by Barnes may extend as far caudally as the fifth lumbar segment.

Weil and Lassek (1929) worked out the proportional distribution of the lateral cortico-spinal tract to the segments of the body. By measuring the area of the lateral tract in 10 humans, in whom there had been a hemiplegia due to a lesion of the pons or above, they found that 50 per cent of the tract runs to the cervical segments, 20 per cent to the thoracic, and 30 per cent to the lumbar segments.

Other species.—It was shown by Bregmann (1915) that in the elephant two-thirds of the fibres of the tract go to supply the seventh cranial nerve for the trunk, the remaining third supplying the spinal cord. In the macaque Peele (1942, 1944) found that the part of the tract originating in area 7 runs only into the cervical cord, and that the axons from all other cortical areas run throughout the length of the cord. Walberg and Brodal (1953) found that in the cat the fibres they described as originating in the temporal and occipital lobes terminate in the

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cervical as well as the lumbar enlargement; it was probable that they also supplied the intermediate parts of the cord.

Summary.—In man, the evidence, though still somewhat inadequate, shows that the lateral cortico-spinal tract runs to the zona intermedia of the grey matter. The ventral tract runs to the anterior horns of both sides; what proportion crosses the cord is unknown. With regard to the caudal extent of the tract, it is known that both the uncrossed and the crossed lateral tracts extend throughout the cord, and that the extent of the ventral tract varies from subject to subject.

With regard to the termination of the lateral tract related to the grey matter, it is known that in the macaque, baboon, chimpanzee, dog and cat, it terminates in the zona intermedia, largely at the base of the posterior horn.

Lamination and Grouping of Fibres

Man.—From their work on strychnine and electrical stimulation of the cortex, physiologists have concluded that there must be anatomical arrangement of cells of origin of the cortico-spinal tract corresponding to the functional arrangement as revealed to them by their methods of investigation. However, physiological methods reveal so much variation within one species, and they demonstrate such vagueness of boundaries of the areas devoted to the different limbs and parts of the body, that they need ample confirmation from workers using anatomical methods. Anatomical work has not revealed the kind of basis which the physiologists expected.

Internal capsule.—From the precentral gyrus, the fibres come together to form a band on the internal capsule. To narrow down to pass through a band-like gap, the fibres undergo a screw-like gyration, the fibres from the inferior part of the gyrus coming to lie most medially, and those from the paracentral lobule coming to lie most laterally. It was established by Dejerine (1901), on the basis of 53 cases, and by Pfeifer (1934) on the basis of myelogenetic studies, that the fibres from the "rolandic operculum" and the adjacent frontal operculum are in the genu of the internal capsule and in the most anterior part of the posterior segment of the capsule. Dejerine considers these as a separate bundle, which he named the "faisceau geniculé." Pfeifer showed that there is intermingling between the fibres running to the cranial nerve nuclei, the cortico-bulbar tract, with descending cortico-thalamic fibres. Behind the cortico-bulbar fibres, it was shown by Dejerine and Pfeifer, there run the fibres, for the hands, arm, and shoulder, and then those for the trunk, thigh, and leg, and most posteriorly, those for the foot.

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Pfeifer from myelogenetic studies was able to show that within the capsule the fibres are arranged antero-posteriorly as follows: fronto-pontine fibres; fibres from area 8, from area 6, then fibres from area 4. Minckler, Klemme and Minckler (1944) showed in their case that the fibres from area 6 remain together in the internal capsule, and that they are situated in the posterior limb about 1 cm. posterior to the genu.

Cerebral peduncle.—Hoche (1900) reported the case of a small tumour situated in the middle of the precentral gyrus, involving the subjacent white matter to a depth of 2 cm. The consequent degeneration in the tract was situated within a triangular area of the crus, the base on the periphery, the apex touching the substantia nigra. He concluded that this area occupied the medial third seventh of the crus. Fischer (1905) reported the case of a tuberculoma as big as a hazel-nut at the superior extremity of the precentral gyrus; the same area of the crus was degenerate as was degenerate in Hoche's case with involvement of the middle region of the precentral gyrus. In Gierlich's (1910) case of a cyst in the paracentral lobule as big as a hazel-nut, the area of degeneration was lateral to that observed by Hoche and Fischer; it formed a triangle in the fourth and lateral part of the third seventh of the transverse area of the crus, passing medio-laterally. Sand (1903) from an examination of 5 cases concluded that the cortico-bulbar together with the cortico-pontine tract occupies the second medial sixth of the crus.

In 1901 Dejerine published his evidence of the anatomy of the crus, consisting of degeneration studies from 53 cases. He assigned the lateral fifth to the temporo-pontine tract, and the medial fifth to the fronto-pontine tract and the cortico-bulbar tract. Within the medial four-fifths of the peduncle he reckoned the fibres were arranged as follows: most medial are those for the face, pharynx and larynx; the fibres for the upper limb come next, occupying the medial second and third fifths; those for the foot are most lateral, occupying the next fifth. He considered that there was much overlap. He wrote: "Il n'existe donc pas dans le pied du pédoncule cérébral, comme le veulent certains auteurs, un faisceau cortico-protubérential (cortico-pontine) distinct, un faisceau des nerfs moteurs craniens distinct, un faisceau pyramidal distinct. Ces fibres sont intimement enchevêtrées les unes avec les autres." This was denied by Flechsig (1905). He wrote that Arnold's bundle does not mix with the pyramidal fibres, and that the cortico-spinal tract occupies only the third quarter from the mid-line. He considered that Dejerine had come to a wrong conclusion, as his lesions were so large that they were never restricted to a single tract. Flechsig emphasized that in any controversy between views based on degeneration following pathological

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lesions and views based on myelogenesis, the former must bow to the latter. This would seem to be right. His remarks on the Vogts drawing conclusions from animal experimentation rather than from myelogenetic studies on *man* have also not lost their point. Von Monakow (1905) from his large experience of pathological material, concluded that the middle third of the pes is occupied by the cortico-spinal tract.

Quensel (1910) investigated the peduncle on the basis of pathological material. He came to the conclusion that the medial half is occupied by the fronto-pontine tract. It is unclear, from reading his paper, how he knew what the fronto-pontine tract was; it seems that he included all the fibres in the crus from the frontal lobe, except those originating in the precentral gyrus.

Two important contributions to our knowledge of the position and relations of the tract in this region have been made in recent years. Minckler, Klemme and Minckler (1944) showed in a diagram the position of the fibres that take origin in area 6. They are shown as occupying the second quarter from the mid-line. They wrote that these fibres occupied "the part of the basis pedunculi assigned to cortico-bulbar fibres"; some of them were in fact cortico-bulbar, but others continued down into the cord. Mrs. Beck (1950) has shown from her careful studies of brains from 33 cases of leucotomy that the fronto-pontine tract is restricted to the medial sixth of the peduncle, and that it does not occupy the whole of this sixth. The medial fifth contains fibres originating in area 6.

Pons.—In Hoche's case of a tumour affecting only the contralateral forearm and hand, the most medial fascicles were free from degenerating fibres, but all the other fascicles contained them. In Gierlich's case of a monoplegia of the lower limb, the degeneration was scattered among all the fascicles. Potts and Weisenburg (1910) reported a case in which a tumour was situated "in the upper portion of the precentral convolution"; it primarily paralysed the face and upper limb, and only latterly caused some paresis of the lower limb. They found that the degeneration in the pons "was confined entirely to those near the raphe." In Minckler, Klemme and Minckler's case the degenerating fibres taking origin in area 6 ran in the fascicles near the median raphe. In fact, they occupied those fascicles which had been spared in the case of Hoche.

Medulla oblongata.—From their great experience the Dejerines came to the conclusion (1904) that wherever the lesion—"qu'elle soit corticale, central ou protubérentielle" and however severe it is, the degeneration is always diffuse in the pyramid. They stated that this opinion was supported by the degeneration found by all staining methods. Cases

reported by Hoche (1900), Marie and Idelsohn (1904), Fischer (1905), and Potts and Weisenburg (1910) all lent support to this view. Van Valkenburg (1913), however, reported a case of a tumour in the same position as the tuberculoma reported by Fischer. He investigated the degenerating cortico-spinal tract using the Marchi technique, which had also been used by Hoche, Marie and Idelsohn, and Fischer, and he also found the degenerating fibres scattered throughout the pyramid; but when he used methods designed to show gliosis, he found that, although there was some gliosis throughout the total region occupied by the tract, it was most intense in the medial two-thirds of the pyramid. Yet in another case, that of a patient in whom one of the branches of the anterior cerebral artery had been blocked when the subject was 1 year old causing a monoplegia of the lower limb, and who died at the age of 34, he found no localization of the degeneration in the pes, pons or medulla oblongata. In the case reported by Minckler, Klemme and Minckler, "at the level of the pyramids, the fibres appear to scatter throughout the cortico-spinal field."

Spinal cord.—Hoche's (1900) case showed general scattering of the degeneration throughout the region of the cortico-spinal tract. Von Szigethy (1925) reported a case of bilateral softening of the paracentral lobules affecting only the lower limbs; in the medulla oblongata and in the thoracic region of the cord the degeneration was spread diffusely throughout the tract, and it was also throughout the ventral tract. In Minckler, Klemme and Minckler's case all the fibres originating in area 6 passed into the ventral tract. Foerster (1936) considered that there was very definite lamination in the tract in the spinal cord. He presented a diagram of this lamination in Vol. V of the Handbuch, but he failed to present any evidence in support of his beliefs.

Other species.—There is evidence that there is almost no topographical arrangement of the fibres of this tract in the dog and in the monkey. Sherrington studied this question in 1885 in the dog and in 1889 in the macaque. He concluded that fibres from cortical "arm-areas" or "leg-areas" were not to be found grouped separately in the cord. "After a cortical lesion of even less than 30 sq. mm. extent the degeneration was found scattered over the whole transverse area of the tract. The only evidence of a localized grouping of the fibres from the cortex to the cord lay in the fact that the more medial and anterior lesions in the so-called motor cortex were followed by degeneration which in the cervical cord was especially severe in those portions of the pyramidal tract abutting upon the direct cerebellar tract. Whereas after lesions in the more lateral and more posterior districts of the motor

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cortex those portions of the pyramidal tract which abut upon the cerebellar tract suffered less.

It was found that after a lesion in the leg-area, encroaching little if at all upon the cortex of the arm-area, the degeneration in the cord stopped short in great part in the cervical region, especially in the cervical enlargement.

Again, after a lesion in the arm-area, encroaching little if at all upon the cortex of the leg-area, the degeneration in the cord extended down through the dorsal into the lumbar and even throughout the sacral region of the cord."

Sherrington returned to the subject in 1893, reporting similar experiments in the dog as well as the monkey. "In the pyramidal tract, and more so in that tract in the dog than the ape, . . . when a degeneration in the tract results from the removal of a small portion of the motor area of the cortex cerebri . . . the fibres are scattered over the whole of the area occupied by the pyramidal tract."

In 1917, in company with Leyton, he made further observations on the arrangement of this tract, on this occasion on an anthropoid ape, namely the chimpanzee. In two chimpanzees the arm-area was excised. In one, degeneration was still present in the lateral cortico-spinal tract at the twelfth thoracic segment, and in the other at the third lumbar segment. With regard to the arrangement in the pyramids, they reported that the degenerated fibres were scattered throughout the area; in one, however, there was nevertheless slightly less degeneration "in the extreme ventro-lateral portion of the cross-section" of the pyramids. In the two chimpanzees in which the arm-area was excised from the cortex, the degeneration was also scattered throughout the pyramid; in the decussation itself, some of the degenerated fibres were among those crossing most cranially.

Mellus (1894) confirmed Sherrington's anatomical findings in the bonnet monkey (*Macacus sinicus*). He found that following excision of an area of 0·4 cm^2. of the left electrically excitable motor cortex subserving movements of the big toe, "the degenerated fibres were scattered throughout the entire area of the crossed or lateral pyramidal tract," although "it might be said they were a little more dense posteriorly." He also found degenerating fibres in both lateral columns at the third thoracic segment following excision of a cortical area serving the left thumb.

In 1907 Simpson and Jolly reported a careful study of lamination and grouping of the fibres of the tract in *Macacus rhesus* and callithrix. "In the highest levels of the internal capsule there is already considerable

overlapping"; this was found to increase as the crus was reached. After excision of parts of the precentral gyrus stimulation of which gave movements of the lower limb, the degeneration was scattered in the pontine bundles in the same manner as when the whole precentral gyrus was excised. Also in the medulla oblongata and spinal cord the degenerated fibres were scattered throughout. "The only noteworthy point is the fact that although the cortical lesion was limited to the leg area, a few fibres can be seen to enter the grey matter of the cord in the cervical enlargement, and the motor tract suffers some loss as it traverses this region." After excision of the arm-area of the precentral gyrus, in the crus the medial fifth and the lateral two-fifths contained only a few degenerate fibres. But in the pons, the medulla oblongata and the pyramid, the degeneration was the same as that found when the whole precentral gyrus is excised. In this case, a few fibres could be traced to the lower end of the sacral cord. Even after excision of the face area, some fibres were traced to the last sacral segment. They then excised from the precentral gyrus various areas, stimulation of which gave movements of the toes, flexion of the knee, flexion of the hip, rotation of the arm, flexion of the wrist, flexion of the fingers, and opening of the mouth. From these experiments they concluded: "It is sufficient to say that below the level of the mid-brain there is no evidence of any localization of the fibres within the area of the pyramidal tract in transverse sections. In the pons, medulla oblongata, and spinal cord they are practically evenly distributed over this area. . . In the case of the limited lesions within the face area some fibres pass into the pyramidal tract of both sides of the cord, crossed and uncrossed, and can be followed to the second thoracic segment, but not beyond it."

In 1937, Häggqvist also found in the macaque that there is no grouping of fibres in the medulla oblongata according to their cervical or lumbar destination.

In 1950, Glees and Cole found the degeneration consequent on small lesions in the thumb and hand areas of the cortex of the macaque and a mangabey. They reported their findings of degeneration down to the lumbar region as a new discovery.

But Woodburne (1939), who worked on the rat, found definite topographical arrangement throughout the tract. The arrangement above the mid-brain is similar to that found in man and other mammals. In the rat, Woodburne found that in the pyramid the fibres to the neck lie most dorsal, those to the lower limbs most ventral, and those to the upper limb intermediate between the other two. In the decussation, the most dorsal fibres cross first; in the cord they come to lie most laterally; they

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are followed by the fibres to the upper limb; the most caudal crossing fibres are those to the neck, and they lie most medially in the cord.

Summary.—To the anatomist, a tract consists of nerve fibres; what movements may be obtained from stimulation of areas of cortex or the cut surface of a tract or tracts is not primarily his concern. If a small lesion made in the cortex causes axons to degenerate throughout the length of the spinal cord, the anatomist must conclude that the cells in which there is a lesion gave rise to fibres descending throughout the cord. If physiologists stimulate this same region and obtain movements from the upper limb and not from the lower limb, the anatomist must still describe this tract as arising in that region of cortex and terminating in the distal part of the cord. It remains a physiological problem to account for the discrepancies between the two types of evidence.

In man, there is lamination of the fibres in the internal capsule; the fibres are grouped according to their destination, (although there is some overlap), and also according to different cortical architectonic origins. Within the crus there is some overlap, although there is still a preponderance of fibres for the lower limb lying most laterally and those for the face lying most medially. Regarding the grouping of the fibres in the pons, the evidence, such as it is, is contradictory. In the medulla oblongata and the spinal cord, there is no lamination. The amount of material from which to draw conclusions in man is very small; undoubtedly many useful cases are wasted, as microscopical anatomical investigations are not carried out.

In monkeys, there is some intermingling of fibres throughout the tract; this includes the cells of origin. For there is much evidence that excision of the "face area" causes degeneration as far as the sacral region of the cord; excision of the "arm area" causes the same degeneration; and excision of the "leg area" causes degeneration in fibres which run into the grey matter of the cervical enlargement. There is considerable overlapping of the fibres in the internal capsule, and more in the crus. In the pons and in all regions caudal to this, intermingling is complete.

Intermingling of Tracts

Man.—In the internal capsule the cortico-spinal fibres are intermingled with numbers of cortico-petal and cortico-fugal fibres, and particularly with fibres running between the cortex and the thalamus. According to Dejerine (1901) the medial fifth of the pes is occupied by the cortico-bulbar fibres, originating in the operculum and the foot of the third frontal convolution, by fronto-pontine fibres, and by "des rares fibres pyramidales."

With regard to the pyramid itself, it has usually been found free from fibres after hemispherectomy. Lassek and Evans (1945), however, reported a case of hemispherectomy; in the ipsilateral pyramid they found two groups of fibres remaining. There were small "mostly myelinated" fibres which "appeared to enter the pyramid from the region of the inferior olivary nucleus and run toward the arcuate nucleus or ventral external arcuate bundle which they join." There were also a "very few scattered fibres which apparently take a directly descending course." In their report of the spinal cord of the same case (1946), they stated that "the pyramidal tract area of the spinal cord contains many axons." They were present in both the lateral and ventral divisions of the tract. "They seem to become more abundant per unit area as one descends the spinal cord and they form roughly 20 to 30 per cent of the fibres in the pyramidal tract area at the level of thoracic five. They probably form between 5 and 10 per cent of all the fibres coursing in the area of the ventral cortico-spinal tract." Lassek performed a bilateral hemispherectomy in a cat, and found such fibres still present. Lassek and Evans (1946) conclude: "It may eventually be proved that the pyramidal tract does not utilize all of the pyramidal tract area in the cord." In fact, this is an old observation, and has often been repeated. It has also frequently been noticed that in the area of the crossed lateral cortico-spinal tract degeneration is more marked after a medullary lesion or hemisection of the cord than after a cortical or a subcortical lesion, even when the latter lesion is massive. This is usually taken to indicate that the region of the tract in the cord contains fibres other than cortico-spinal. This is probable. But one needs to remember that the area of the tract within the cord is not the same in all specimens, that the size of transverse sections of the cord varies greatly, and that the amount of shrinkage of the material is dependent on many factors, all of which must be known and controlled, before comparison between sections from different cases can be made. However, apart from such factors, many lesions of the cord which involve the region of the cortico-spinal tract may involve also the region of the rubro-spinal tract (if such exists in man) whereas lesions above the red nucleus, or even above the cortico-spinal decussation will not do so. Further, the area of the lateral cortico-spinal tract contains also ascending and descending spino-spinal fibres. It seems that any surgical lesion made at a spinal level intended to divide the lateral cortico-spinal tract is bound to divide also the dorsal spino-cerebellar tract and spino-spinal fibres, and possibly also the rubro-spinal tract.

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The fibres of the ventral cortico-spinal tract are mingled with those of the median longitudinal fasciculus.

Myelination, Size and Number of Fibres

Man.—According to von Monakow (1905), some myelination has started in the 10–14 day old baby; it is present in the internal capsule and peduncles. Myelination is completed in the second year. It proceeds simultaneously in the lateral and ventral divisions of the tract. Flechsig (1905) found that the axons from the paracentral lobule and from the upper third of the precentral gyrus myelinate before those from the middle third of this gyrus.

Before turning to the matter of counts on the fibres of this tract, it may well be of importance to bring up the question of the dividing of axons. In 1889, Sherrington described what he called "geminal fibres"; he noted that both divisions of a dividing nerve are of equal size, and that they are of the same size as the parent axon. In 1892 he devoted a short paper to the subject. He observed the branching of medullated fibres in the cortico-spinal tract in the brain and cord of man, monkey and dog. He also found such fibres in the corpus callosum, dorsal spino-cerebellar tract, the antero-lateral tract and the posterior columns. The geminal fibres measured between 3 and 15 μ. He considered that "under geminal fibres there will probably have to be included varieties—bigeminal, trigeminal, etc." No notice seems to have been taken of these observations, in spite of the integrity of their originator. If there is such a dividing of fibres, all the relationships deduced between counts of cells and counts of fibres, are wrong.

There is also the question of collaterals, in this and in other tracts. Collaterals were discovered by Golgi, and were investigated mainly by Cajal. Over the past quarter of a century it has been usual to omit reference to collaterals of long tracts; but the evidence of earlier workers would seem to indicate that such exist. Soury (1899) discusses this question, and concludes: "En thèse général, il n'y a pas de fibres pyramidales sans collatérales, et le nombre de celles-ci est proportionnel à l'épiasseur de ces fibres motrices." Apart from the significance of such collaterals for function, their existence would again cause misinterpretation of fibre counts.

The first worker to count the fibres of this tract was van der Bruggen (1930). He made specimen counts of various areas of the tract "at the level of the olive." The ages of the subjects varied between $2\frac{1}{2}$ and 93 years. He concluded that the normal tract at this level contains 150,000 fibres. They were next counted by Lassek and Rasmussen

(1939, 1940) in 3 young adults; they found "just rostral to the motor decussation," 1,100,000 fibres. The largest number of counts has been made by Verhaart. In 1947 he reported counts on the pyramids of 23 subjects between the ages of 20 and 50. His figures were as follows:

Fibres about 1 μ: 700,000—1,200,000;
Fibres from 2 to 3 μ: 23,000—70,000;
Fibres from 3 to 5 μ: 21,000—51,000;
Fibres from 5 to 8 μ: 11,000—18,000;
Fibres larger than 8 μ: 2,600—5,400.

He comments: "The wide differences in number of the fibre groups in different normal pyramids has never been emphasized till now; but as far as I know, no single author has counted so many pyramids yet." In a later paper (1950) Verhaart reported the result of counting both pyramids in 3 further normals and one pyramid in 3 other adults with lesions acquired late in life affecting the other pyramid. In some respects the figures differed greatly from those given above, and yet Verhaart made no comment on this difference; for example, in the later paper, the maximum number of fibres about 1μ was 645,000, about half the previous figure given. In a further paper (1952) Verhaart and Kramer gave the figure for the total number of fibres in the tract as varying between 600,000 and 1,000,000.

A factor which has to be noted in counting the fibres in the medulla oblongata was pointed out by Glees, Liddell and Phillips (1951): some of the ascending fibres subserving sensation lie between the olive and the cortico-spinal tract. It is possible that those who have counted the axons of the cortico-spinal tract may sometimes have been misled and counted these afferent axons in with those of the cortico-spinal tract. Flechsig (1881) had already drawn attention to this point and had stated that the two could be distinguished, as the cortico-spinal tract contains "far thinner fibres."

Flechsig (1876) in his original account of the tract stated that the spectrum of fibre size is very wide, and that this tract contains some of the largest and some of the smallest fibres of the cord; he also stated that most of the fibres are of very fine type. As can be seen from the figures given by Verhaart, more recent work confirms and enlarges Flechsig's observations. Häggqvist (1937) measured the fibres in a girl aged 13; he found that they measured between 1 and 21 μ. According to Lassek and Rasmussen, "just rostral to the motor decussation" over a half of the fibres are less than 1 μ, and over 80 per cent are less than 3 μ; there are a few large fibres measuring 10 to 25 μ. According

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to Verhaart (1947): "The medullary pyramid in man consists of fibres ranging from 1 μ to 20 μ in diameter, the medullary sheaths included." All authors agree in stating that the various sizes of fibres are equally dispersed throughout the tract and occur in the lateral and ventral divisions of the tract.

Szentagothai-Schimert (1941) showed from his counts on human material that the fibre spectrum of the tract varies considerably with the level at which the count is made. He found, for instance, that at the fifth thoracic segment 10 per cent of the fibres measured 1 μ, whereas at the second cervical segment 35 per cent did, and in the medulla 45 per cent did. At the fifth thoracic segment, the greatest number of fibres measured 3 μ, whereas the greatest number are 1 μ in the crus, the medulla oblongata and the second cervical segment.

In the newborn infant there are no thick fibres in this tract. The diameter of the thickest fibres at various ages is given by Verhaart (1950).

These are given in the following table.

DIAMETER OF THICKEST FIBRES IN THE PYRAMID

Age of child in years	*Diameter of fibres in mμ.*
Neonatus	1
1/3	3
2/3	4
1½	5
2	7
3	9
4	10
7	12

Häggqvist (1937) showed that the thicker fibres run to the lumbar and sacral regions.

Summary.—Myelination starts during the first month of extra-uterine life and is complete in the second year. Counts have been made on the cells and fibres of this tract without regard being paid to the possibility of the branching of axons. This applies to all counts made on all tracts. It may, or it may not, render them meaningless. The figures of the counts of the axons of the cortico-spinal tract given by various authorities differ greatly. It is certain, however, that the tract consists for the most part of small fibres, most of them measuring about 1 μ; there are a few large fibres, measuring from 10 to 25 μ, the largest running to the lumbar and sacral regions.

MEDIAN LONGITUDINAL BUNDLE

Before the introduction of the B.N.A. the median longitudinal bundle was called the posterior or dorsal longitudinal bundle or the fasciculus commissuræ posterioris.

This is a very old tract phylogenetically. It comprises ascending and descending bundles; only the latter will be reviewed here. In those mammals in which a reticulo-spinal tract has been described, it has been found that a ventral group of the reticulo-spinal tract runs in the median longitudinal bundle. This was first found by Probst in the dog (1899). In some of the literature this tract is considered as a part of the reticulo-spinal tract, elsewhere as a part of the median longitudinal bundle. Here it will be considered in the section of the reticulo-spinal tract.

Degeneration studies are unlikely to be useful for such a small tract as the median longitudinal bundle, running, as it does, in regions so crowded with tracts. Its degeneration in man was first recorded by Fusari (1896); in this case, as in all subsequent cases, the lesion involved not only this tract, but surrounding structures and tracts; here the reticulo-spinal tract and probably the central tegmental tract were also involved. Ceni (1898) reported a case in which a hæmorrhage had involved the lateral part of the bundle. Although this was such a long-standing lesion that the Weigert-Pal technique had to be used, Ceni was able to trace the degeneration into the anterior column of the cord. In the case of Gee and Tooth (1898), where the Marchi technique could be used, the hæmorrhage involved both medial longitudinal bundles and a considerable part of the reticular substance. They were unable to separate the various tracts near the median raphe; the tract marked in their drawings as the posterior longitudinal bundle includes the area occupied by the central tegmental tract, the tecto-spinal tract, and the reticulo-spinal tract (in the mammals in which these tracts are known to exist). Indeed, the fact that they traced degenerate fibres into the olive shows that such fibres were those of the central tegmental tract. Yet when one compares the degenerating fibres running along the floor of the fourth ventricle medial and anterior to the seventh nucleus, which in more caudal sections runs along the median raphe, with a tract occupying the same position in lower mammals, it would seem most likely that these fibres are indeed those of the median longitudinal bundle. Spitzer (1899) was also able to use the Marchi method in his case of a tuberculoma causing degeneration in both median longitudinal bundles. He showed that in man this bundle contains more descending than ascending fibres.

Cells of Origin

Man.—The cells of origin of this tract in man are not fully known. Spitzer (1899) showed that the descending fibres originated in the nuclei of the third, fourth and sixth nerves, and in the lateral vestibular

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nucleus; it seemed likely that some fibres originated also in the reticular substance. Tsuchida (1906) found the same origins as Spitzer; he added to this list fibres taking origin in the distal part of the substantia gelatinosa of the fifth cranial nerve; his observations were made on one human case and on human embryos. With regard to the nuclei of the third, fourth and sixth cranial nerves, he showed that the fibres of the bundle do not arise from the main motor cells, but from smaller cells.

Stengel (1924) and Ingram and Ranson (1935) studied in detail the human nucleus of Darkschewitsch (also called the nucleus of the fasciculus longitudinalis posterior, the nucleus of the posterior commissure, the nucleus antero-lateralis, the nucleus dorsalis) and the nucleus interstitialis of Cajal; however, they were not concerned with the tracts related to these nuclei. The nucleus interstitialis consists of large multipolar cells, and the nucleus of Darkschewitsch of small cells. Foerster and Gagel (1932) searched for retrograde cell changes in the nucleus of Darkschewitsch after antero-lateral cordotomy, but found none. Lucas Keene and Hewer (1933) showed that in human embryological material the median longitudinal bundle receives fibres from the third and fourth cranial nerve nuclei and descending fibres from the lateral vestibular nucleus and the superior olive. Savas (1954) has shown that the descending fibres of the tract originate in the nucleus interstitialis, the nucleus of Darkschewitsch, the medial, lateral, and descending vestibular nuclei. He considers it likely that the axons of the nucleus of Darkschewitsch do not descend into the spinal cord.

Other species.—The cells of origin have been determined in the rabbit, the dog, the cat, and the monkey. In these mammals it is known that the cells of origin are (enumerated cranio-caudally) as follows: the nucleus of Darkschewitsch; the nucleus interstitialis: periaqueductal cells; the nuclei of the third, fourth, sixth, seventh, and eleventh cranial nerves; the descending nucleus of the fifth cranial nerve, the medial, lateral, superior and descending vestibular nuclei, the dorsal nucleus of the vagus, and the nucleus ambiguus; reticular cells of the mesencephalon and pontine regions, including the magnocellular nucleus. The fibres from the cranial nerve nuclei run both ipsi- and contra-laterally.

Fraser (1901) working on the monkey, dog, and the cat, found that most of the descending fibres originate in the lateral vestibular nucleus. Rasmussen (1930) stated that in the cat this nucleus does not give rise to descending fibres, but in 1932 he found that some cells in the nucleus do apparently give rise to descending fibres. Most workers consider that some axons arise in the superior colliculus; but Tasiro (1940) found no evidence from his careful work on the cat to support this.

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Course

Man.—The tract consists of both ipsi- and contra-laterally running axons.

The course, as given here, is taken from the case reported by Gee and Tooth (1898), from Cases 1, 2 and 3 of Collier and Buzzard (1901), from the case reported by Roussy (1907) and by Long and Roussy (1908), from the study by Weisschedel (1937) and that of Savas (1954).

The tract is small in the cranial parts of the mid-brain, and becomes larger and more conspicuous as it descends through the pons; in the medulla oblongata it becomes obscured, by being mixed with the tecto-spinal tract and the fibres of the medial lemniscus; also in the cord it is inconspicuous, as it comes to form a part of the sulco-marginal tract.

The tract retains an anterior relation to the cranial nerve nuclei throughout its cranial course. At first, travelling cranio-caudally, it is posterior and then medial to the red nucleus, and it serves to make up the medial part of the capsule of this structure. It then forms the antero-lateral border of the third nerve nucleus; here in transverse sections through the caudal extremity of the red nucleus it can be seen to form a V with its fellow of the opposite side. Immediately lateral to it is the central tegmental tract. Throughout the mid-brain it is separated from the floor of the aqueduct by the periaqueductal grey matter; in the pons, the tract spreads out laterally, so that it forms the anterior border of the periaqueductal grey matter; further caudally, where the periaqueductal grey matter has ceased, this tract lies beneath the aqueduct and the floor of the fourth ventricle; it is separated from its fellow of the opposite side by the median raphe. It lies posterior to the superior central reticular nucleus, and posterior to the tecto-spinal tract. This relation to the tecto-spinal tract remains the same throughout the brain; both abut against the median raphe, the median longitudinal bundle lying posterior to the tecto-spinal tract. In the medulla the two tracts are poorly demarcated from the ascending fibres of the median lemniscus. Caudal to the vestibular nuclei, the median longitudinal bundle and the tecto-spinal tract become more anterior, as they descend. At the level of the inferior olive, they lie in the centre of the medulla oblongata, surrounded on all sides by the fibres of the median lemniscus. Immediately caudal to the cortico-spinal decussation, the fibres of the bundle are shown by Roussy as situated between the anterior horn and the median fissure; Roussy states that they lie lateral to the area of the ventral cortico-spinal tract. They remain lateral to this tract at the third cervical segment, but by the third thoracic segment these two tracts become mingled.

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Termination: Relation to Grey Matter

Man.—Spitzer (1899) considered that in his case the axons arising in the cranial nerve nuclei 3, 4 and 6 and the lateral vestibular nucleus run to the anterior horns of the cervical cord. It seems that there is no other evidence in man of the distribution of this tract.

It should be pointed out that, when fibres are described as ending in the anterior horns, this implies no anatomical or functional connexion with the motor cells of the anterior horns.

Other species.—In the dog, Thomas (1898) traced the fibres of the tract to the anterior horns; Probst (1899) did the same. Szentagothai-Schimert (1941), working on the cat, found that the axons of this tract originate in the lateral vestibular nucleus and around the motor cells of the anterior horn; he found also that there was degeneration in the zona intermedia and the posterior horn, but he considered that this might have resulted from damage to the tecto-spinal or the reticulo-spinal tracts, which were also involved in his lesion.

Termination: Caudal Extent

Man.—Collier and Buzzard stated that the bundle descends into the sacral cord; but they did not distinguish it from the other tracts of the sulco-marginal area. The same criticism applies to the case reported by Gee and Tooth. Marie and Guillain (1903) were unable to trace the tract below the medulla oblongata, but as the lesion was twenty-six years old, the authors attributed no significance to this finding. Long and Roussy (1908) could not trace the tract caudal to the third cervical segment; they were concerned only with that part of the tract that originates in the nucleus of Darkschewitsch. Langworthy (1930) concluded from his embryological material that the tract runs throughout the length of the spinal cord.

Other species.—Probst (1899) found in the dog that some of the fibres descend into the lumbar cord. In the rabbit, it was found by van Gehuchten (1904) that the axons originating in the nucleus of Darkschewitsch, the lateral vestibular nucleus, and in the reticular substance, continue down to the lumbo-sacral region of the cord. Van der Schueren (1912), also working on the rabbit, found that axons arising in the mesencephalic reticular substance also reach the lumbar cord, whereas those from the lateral vestibular nucleus do not descend further than the mid-thoracic region. Hashimoto (1928) who also worked on the rabbit, found that the axons arising in the nucleus of Darkschewitsch descend at least into the cervical cord. Rasmussen (1932) found in the cat that the axons arising in the medial and

descending vestibular nuclei stop in the lower thoracic cord. And Buchanan (1937) found in the cat that the axons arising in the lateral vestibular nucleus running in the contralateral median longitudinal bundle terminate in the cervical cord, whereas those from this nucleus running in the ipsilateral bundle run throughout the length of the cord; the fibres from the descending nucleus, both ipsi- and contralateral, descend into the cervical cord.

Lamination and Grouping of Fibres

Man.—Savas (1954) found that, caudal to the oculo-motor nuclei, the descending fibres from the nucleus interstitialis and the nucleus of Darkschewitsch are most medial in the bundle; lateral to them lie the crossed vestibulo-mesencephalic fibres. At the level of the hypoglossal nucleus, the middle and outer parts of the bundle are formed of descending vestibular fibres; these are both crossed and uncrossed. At the level of the first cervical segment, the various components of the tract are thoroughly intermingled.

Intermingling of Tracts

Man.—This tract is not a single entity, as, for instance, the olivospinal tract; for it has multiple origins, and consists of ascending as well as descending fibres. In the pons, it is joined by the medial reticulospinal tract. Throughout the medulla oblongata its fibres are surrounded by the ascending fibres of the medial lemniscus. In the cord it is mingled with the ventral cortico-spinal tract, the tecto-spinal tract and the vestibulo-spinal tract. These anterior descending tracts were called by Marie "le système descendant de la zone sulco-marginale."

Myelination, Size and Number of Fibres

Man.—Lucas Keene and Hewer (1933) studied this bundle in the human embryo. The bundle could not be found in the 10 mm. embryo; but it was present in that 12 mm. long. Myelination starts between the fourteenth and sixteenth week. They found between the twenty-fourth and twenty-sixth week myelinated connexions with the third nerve nucleus, and also by this time the lateral vestibular nucleus and superior olive had sent descending myelinated axons into the tract. Lucas Keene (1938) later reported that in the 24-week-old embryo there is a myelinated connexion with the nucleus of Darkschewitsch. Langworthy (1930) found that most of the bundle was already myelinated in his 29-week-old embryo.

Flechsig in 1876 described this bundle as consisting of both thick and thin fibres. Muskens (1935) found that the fibres from the nucleus of

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Darkschewitsch are thin, while those from the nucleus interstitialis are thick.

Three workers examined the size of the fibres of this tract in detail: Wohlfart (1940), Szentagothai-Schimert (1941), and Savas (1954). As this tract is not homogeneous, receiving and giving off many axons during its course, the fibre spectrum varies considerably with the location of the count. Schimert gives the following figures: fibres of 1 μ, 22 per cent; of 3 μ, 38 per cent; of 5 μ, 26 per cent; and of 7 μ, 11·5 per cent. Wohlfart found that of the medial part of the tract (which contains the descending fibres) fibres of 1–2 μ form 12 per cent immediately cranial to the pons, and 25 per cent immediately caudal to the pons; fibres of 2–3 μ form 24 per cent immediately cranial to the pons and 14 per cent caudal to the pons; no fibres larger than 7 μ were found. Savas found in the medial part of the tract immediately caudal to the oculo-motor nuclei 79 per cent of the fibres measured 2–5 μ; they formed the majority of the medial part of the bundle throughout its course. In the pons at the level of the facial colliculus, 67 per cent measured 3–5 μ, and 16 per cent, 1–3 μ. Fibres up to 10 μ were found in the lateral and middle parts of the tract. At the first cervical segment, 24 per cent measured 5–10 μ, 67 per cent were 2–5 μ, and only 9 per cent were 1–2 μ. The fibres descending from the vestibular nuclei measured 3–6 μ. Savas also considered that the thick fibres of the medial part of the tract come from the nucleus interstitialis and the thin fibres from the nucleus of Darkschewitsch.

Other species.—Cajal (1896) studied this bundle in the embryo of the mouse; he observed that those fibres that originate in the lateral vestibular nucleus usually consist of a thick ascending division and a thin descending division. Langworthy (1929) observed in the kitten that that portion of the tract which runs into the spinal cord myelinates before the portion connected with the mid-brain.

Tecto-Spinal Tract

In the older literature this tract was sometimes called the predorsal tract or bundle; the predorsal bundle, however, includes the tecto-bulbar tract; and some authors use the term to include other descending fibres. In the older English literature, the tract was sometimes called the colliculo-spinal tract or the ventral longitudinal bundle. In German literature, it was sometimes called the Vierhügelvorderstrangbahn. The cranial part of the tract was named by van Gehuchten le faisceau optique descendant, and by Cajal le faisceau descendant de la callotte.

Held (1890), when working in Flechsig's laboratory, first described

the whole tract, observing it in the embryos of the cat and the rat. This tract is proportionally smaller in mammals than in lower members of the phylogenetic scale. In birds, it consists of both crossed and uncrossed fibres.

Cells of Origin

Man.—Tsuchida (1906) found in newborn babies that the axons arise from the deeper layers of the superior colliculus, in its medial and lateral parts. Foerster and Gagel, however, (1932) looked for cell changes in the colliculi following antero-lateral cordotomy, but found none.

Other species.—Held (1890, 1892) showed that in the rat and the cat the tract originates in the large cells of the middle and deep grey matter of the superior colliculus. Rasmussen (1936) showed in the cat that the axons originate in the "middle strata of the superior collicular region." He found that the cells of origin continue throughout the cranio-caudal extent of the superior colliculus, but Tasiro (1940) found that the tract originates only in the cranial half of the superior colliculus.

Course

Man.—This tract is known to be crossed. There may be in addition a few uncrossed fibres; but no organized uncrossed tract has ever been found in man.

The course of the tract is well shown by Collier and Buzzard (1901) in their Cases 1, 2 and 3. The fibres are first found forming the circumferential boundary of the central grey matter; their decussation forms the dorsal tegmental decussation. After the fibres have crossed the median raphe, they lie immediately anterior to the median longitudinal bundle; they may become mingled with this bundle; this occurs most frequently in the lower medulla oblongata, after the median longitudinal bundle has received its contribution from the vestibular nuclei. The tecto-spinal tract is separated from its fellow of the opposite side only by the median raphe. At the level of the inferior olive, the tract, in company with the median longitudinal bundle, passes more anteriorly, so that caudal to the level of the cortico-spinal decussation, it comes to form a part of the anterior ground bundle. It then descends in the fasciculus sulco-marginalis, between the anterior sulcus and the ventral edge of the anterior column of the cord.

Other species.—It is generally held that in the rabbit and cat there is an uncrossed tecto-spinal tract. It is said to arise in the inferior colliculus. Rasmussen (1936) denies the existence of this tract, and thinks that the descending fibres attributed to it are due to the lack of discreteness of the experimental lesions.

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Termination: Relation to Grey Matter

Man.—This is unknown.

Other species.—In the cat, Redlich (1899) found that the tract runs to the anterior horn cells; Probst (1899) found the same. In 1923, Rasdolsky reported his results from using his light green fuchsin stain in the dog. It is impossible to evaluate this work; for Rasdolsky gave no photographs of his sections, and his work, as far as we can find out, has not been repeated, denied, or confirmed; references are rarely made to his work, and yet, his conclusions are, if true, important. Briefly, he found that the fibres of the cortico-spinal, rubro-spinal, tecto-spinal, vestibulo-spinal tracts and of the median longitudinal bundle, all enter the grey matter to go to cells of the zona intermedia, and that none of them go to the cells of the anterior horn; those fibres that enter the grey matter via the anterior horns, traverse this region in order to terminate in relation to cells of the zona intermedia. He considered that the tecto-spinal tract terminates in the zona intermedia in the same region as the termination of the lateral cortico-spinal and the rubro-spinal tracts. Rasmussen (1936) found in the cat that this tract is distributed mainly to the "motor nuclei in the lower region of the medulla oblongata and ventral horn cells of the upper cervical segments of the spinal cord." Szentagothai-Schimert (1941), having made lesions in the superior colliculus of mice, was able to trace the tract into the medial part of the anterior horn; he found that it continued within the grey matter, ending near the zona intermedia; many fibres could be traced to the ventrally placed cells of the posterior horn, and many ended round the cells of the nucleus cornucommissuralis ventralis.

Termination: Caudal Extent

Man.—Although all the textbooks state that the tract does not descend below the eighth cervical segment, we can find only two positive statements on the subject in man from those who worked on this tract. Collier and Buzzard (1901) traced the fibres into the sacral cord; but it is quite clear that they could not distinguish these fibres from those of the median longitudinal bundle. Wohlfahrt (1932) stated that the tecto-spinal tract in man descends only as far as the cervical cord, but he gave no evidence in support of this statement.

Other species.—In the cat, Boyce (1894) traced the tract into the thoracic segments; actually he did not name the tract, but it is obvious from his work that this is the tract, for it crossed the median raphe in the dorsal tegmental decussation. Tschermak (1898), also in the cat, traced the tract into the lumbar segments; but Redlich (1899) considered that it

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does not descend below the cervical cord. Later workers have found the tract in the cat to have only an unimportant spinal component: Marburg and Warner (1947) state that the predorsal bundle "is almost exhausted at the level of the inferior olive and only single fibres enter the cord"; and Pearce (1953) found that although some fibres reach the first thoracic segment most of the tract does not reach the cord, but runs to the reticular substance of the mid-brain, pons and medulla oblongata.

Intermingling of Tracts

Man.—In the pons and medulla oblongata the tract may be mixed with the median longitudinal bundle. In the cord it is intermingled with the fibres of the vestibulo-spinal tract as well as the median longitudinal bundle.

Myelination, Size and Number of Fibres

Man.—Tsuchida (1906) found in his human material that there is myelination in the fourth month in the dorsal tegmental decussation and in the tecto-spinal tract in the pons. By the fifth month the myelination of the decussation is very marked.

The tract consists of large myelinated fibres. No fibre counts have been made in man.

Rubro-spinal Tract

The rubro-spinal tract was first observed by von Monakow in the rabbit (1883); he did not discover its origin or termination. The tract was therefore often called von Monakow's bundle. André Thomas named it the faisceau prépyramidal, Meynert called it the Ausseres Seitenstrangbündel; in German literature, it is often called the Vierhügelseitenstrangbahn. Pavlov (1900) first named it the rubro-spinal tract.

It seems to be everywhere assumed that there is in man a rubro-spinal tract, just as there is in other mammals. But the evidence for the existence of this tract in man is poor. If the tract exists, it is bound to be small; for the cells which would give it origin are few.

Von Monakow, who first described the tract in any species, considered that the existence of a "rubro-spinal" tract caudal to the sensory decussation in the medulla, had not been satisfactorily shown in man (1905). He recorded that he had examined many cases in which there was a severe disturbance of the red nucleus and yet the opposite lateral column of the cord was completely normal. The tract has often not been found in Weigert preparations; but as it must be small, this need not lead to doubt of its existence. Workers using Weigert staining who

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looked for, but did not find, this tract were Ceni (1898), von Halban and Infeld (1902), Marie and Guillain (1903), Tsuchida (1906), and Souques, Crouzon and Bertrand (1930).

But other workers have also failed to find this tract, although they used the Marchi technique. Raymond and Cestan (1902) reported a case in which a tumour involved the whole of the left red nucleus and the medial part of the right. The patient died four months after the onset of the symptoms, and so the Marchi technique could be used. Although the authors were well aware of the importance of their case, they had to admit that "Il nous a été impossible de trouver un faisceau rubro-spinal." Long and Roussy (1908) were unable to find any evidence of a rubro-spinal tract in their Marchi sections of a case with a lesion involving the red nucleus.

Holmes (1904) reported that he found considerable "degeneration in the position of the rubro-spinal tracts" in 2 cases; but as he was not concerned with anatomical questions in this paper, he presented no photographs or drawings.

Collier and Buzzard (1901) reported 2 cases stained with the Marchi technique in which they found degeneration of the rubro-spinal tract. In their first case the decussation of the tracts "in Forel's decussation was plainly seen. . . In the region of the decussation of the pyramids they were situated far more dorsally and deeper than in the cat and monkey and were ventral to the substantia gelatinosa." The fibres were large and few. In their second case, they showed the tract marked clearly in their drawings. It must be pointed out, however, that there was also degeneration of the cortico-spinal tract; the difference in area of degeneration of the cortico-spinal tract on transverse section varies a great deal from one case to the next; and so conclusions may not be drawn about the rubro-spinal tract unless there is no degeneration of the cortico-spinal tract. Collier and Buzzard stated that they did not find this tract degenerate in all the cases in which there was damage to the red nucleus.

Winkler (1929) stated that there is in man a tract running in the position of the rubro-spinal tract in lower mammals at least as far caudal as the medulla oblongata; for he found that in cases of thrombosis of the posterior inferior cerebellar artery or of a syringomyelic cavity in the same region, there is atrophy of all the cells of the pars magnocellularis.

Langworthy (1930) in a 29-week-old human embryo found no evidence of a rubro-spinal tract; either it was not yet myelinated, or it is not present in man.

André Thomas (1936) reported a case in which a lesion involved both

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red nuclei, the median longitudinal bundle, the nuclei and roots of the third nerve and the substantia nigra. Although he used the Marchi technique, he found no evidence of a rubro-spinal tract.

Weisschedel (1937) showed beautiful photographs of the brain of an anencephalic in which the decussation of the rubro-spinal tracts in the ventral tegmental decussation can be clearly seen. He was not concerned, however, in tracing the tract into the cord.

The most important case is the first case of Stern's (1938). Following a total lesion of the cord in the upper thoracic region, retrograde changes were found in the magnocellular part of both red nuclei. Similar changes were also found in his second case, a case of thrombosis of the posterior inferior cerebellar artery. Stern's first case remains the most important piece of positive evidence that there is in man, a rubro-spinal tract descending into the spinal cord at least as far as the upper thoracic cord.

Mussen (1929) showed that there is in the cat a tract which he named the rubro-cervical tract. It arises in the parvocellular part of the red nucleus; its fibres then run into the magnocellular part and decussate in the anterior part of the ventral tegmental decussation; they remain anterior to the fibres of the rubro-spinal tract; they terminate in the cervical cord. There is no evidence for the existence of such a tract in man.

Summary.—It is not yet adequately known whether the rubro-spinal tract exists in man. Stern's work is sometimes quoted as evidence for the existence of this tract. His second case provides no information of the existence of a rubro-spinal tract; it showed that there are fibres originating in the red nucleus that descend as far as the medulla oblongata; no work was done to trace degenerating fibres into the cord. Stern's first case provides positive evidence; against it, we have the following four observations: Foerster and Gagel failed to find retrograde changes following antero-lateral and anterior cordotomies; using the Marchi technique, Raymond and Cestan, Long and Roussy, and André Thomas, all failed to find the tract in suitable material.

Cells of Origin

Man.—Foerster and Gagel failed to find any retrograde cell changes. However, Stern (1938), in his first case, found typical retrograde chromatolytic changes in the magnocellular part of the red nucleus. The same changes were seen in his second case; but, the lesion being a medullary one, it is impossible to talk of a rubro-spinal tract.

Other species.—It was first demonstrated by Held (1890), in his

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study carried out in Flechsig's laboratory, on the embryos of the rat and cat, that von Monakow's bundle originated in the red nucleus. Probst (1899) confirmed this work, by making lesions in the red nucleus of the dog and cat and tracing descending degeneration.

Cooper and Sherrington (1940) found chromatolysis in a "small compact group of large cells ventrolateral to the most ventral part of the ocular nucleus" in the macaque's pars magnocellularis of the red nucleus; these changes were on the side opposite to hemisections of the spinal cord carried out at the fourth and fifth cervical segments.

Course

Man.—The fibres of the tract, as they leave the red nucleus, make up a part of the capsule of this nucleus. Little more is known of the course of the tract in man.

Other species.—The description of the course which follows is a general scheme, applicable to most mammals.

Bodian (1946) showed in *Macacus rhesus* that the tract is largely crossed; he found that probably 7 per cent of the fibres at the level of the first cervical segment come from the ipsilateral nucleus. Cooper and Sherrington found no changes in the ipsilateral nucleus in the macaque.

The fibres, after leaving the capsule of the red nucleus, cross the median raphe, their decussation forming the ventral tegmental decussation. They immediately turn caudally, lying dorsal to the substantia nigra and lateral to the central tegmental tract. As they descend they lie on the dorsal aspect of the medial lemniscus, gradually passing laterally through the antero-lateral part of the substantia reticularis. They lie lateral to the nucleus and roots of the seventh cranial nerve, and dorso-medial to the superior olive; here they separate the transversely running fibres of the corpus trapezoideum; some of the fibres of the latter separate the tract from the periphery. When the tract first comes into relation with the spinal root of the fifth cranial nerve, it lies medial to it. In the medulla oblongata it is separated from the periphery by the external arcuate fibres. At the level of the most cranial part of the cortico-spinal decussation, it is dorsal to the ascending fibres of the spino-thalamic and spino-tectal tracts; further caudally it becomes mingled with them. In the cervical cord, this tract occupies a wedge-shaped area, with its base antero-lateral; the area is medial to the dorsal spino-cerebellar tract, which, according to Rothmann (1900), in the dog, it penetrates; it lies ventro-lateral to the middle of the posterior horn. According to Probst (1899), the tract never extends farther anterior than the posterior commissure of the cord.

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Termination: Relation to Grey Matter

Man.—This is unknown.

Other species.—Risien Russell (1897) in the dog and the macaque found the fibres going into the anterior horn "the bulk of these fibres apparently passing to the part of it known as the lateral horn." He found none going to the opposite anterior horn. Probst (1899) also found, in the dog and the cat, clear evidence of the tract ending between the anterior and posterior horns; this was particularly clearly seen in the cervical and lumbar enlargements. Rothmann (1900), who studied the tract in the dog, also traced the fibres into the grey matter in a "region between the anterior and posterior horns"; but he added that he could not say where the fibres actually ended. Fraser (1902) who worked on the cat and the monkey found that the tract ends by entering "the lateral aspect of the grey matter and then turns forwards in this to break up around the anterior horn cells." Rasdolsky (1923) also found in the dog that the fibres enter the zona intermedia, just anterior to the fibres of the lateral cortico-spinal tract. Szentagothai-Schimert (1941) also found in the cat that the fibres run to the medial part of the zona intermedia. Following lesions destroying the red nucleus, he found degenerating nerve-endings around the cells of the nucleus intermedialis.

Termination: Caudal Extent

Man.—Stern (1938) showed that the fibres reach at least as far as the upper thoracic cord.

Other species.—In the cat, Boyce (1894) traced it into the lumbar segments; in his paper this tract can be identified as it is the tract that crosses in the ventral tegmental decussation; Boyce at that time was unaware of its origin. Rothmann (1900) traced the tract in the dog into the lumbar enlargement; he did not examine it further caudally. Van Gehuchten (1901) traced the tract in the rabbit into the lower sacral cord. Bodian (1946) found in the macaque that half the fibres reach the eighth thoracic segment, and that 18 per cent are still present at the second lumbar segment.

Lamination and Grouping of Fibres

Man.—These are unknown.

Other species.—In the rat, Woodburne (1939) found that "the more fronto-laterally arising fibres cross first to reach the lateral portion of the descending rubro-spinal tract and are succeeded in orderly fashion by more medio-caudally arising fibres which then occupy the medial portion of the tract." In the cord, he thought that the rubro-spinal tract

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was laminated in a latero-medial direction, the longest fibres lying most laterally.

Intermingling of Tracts

Man.—According to Collier and Buzzard, caudal to the vestibular nuclei, the rubro-spinal tract becomes mixed with the vestibulo-spinal tract. Further caudally it mingles with the ascending fibres of the spino-thalamic and spino-tectal tracts.

Myelination, Size and Number of Fibres

Man.—According to Collier and Buzzard, the tract becomes myelinated in the 5th fœtal month.

No fibre counts have been made in man.

Other species.—In the mammals in which this tract has been studied, the fibres are always found to be thick and myelinated.

Reticulo-spinal Tract

In 1885 von Bechterev first described in a human embryo tracts originating in the reticular substance; he called some of them reticulo-spinal, and some ponto-spinal. He traced these fibres into the ventral and the lateral regions of the spinal cord. He also showed that some of the fibres originating in these reticular nuclei are ascending.

It is thought that in man there are at least two divisions of the reticulo-spinal tract: a medial uncrossed (the Bruckenvorderstrangbahn of von Bechterev) and a lateral crossed (the Bruckenseitenstrangbahn of von Bechterev). In addition, Pfeifer (1916) showed in his anencephalic material, that there is a tract arising in the inner part of the reticular substance which crosses the mid-line in the highest cervical region of the cord at the caudal end of the cortico-spinal decussation, and which runs to the anterior horns. Flechsig in a personal communication to Pfeifer reported that he had seen this decussation in human embryos 36–45 cm. long, and that it was myelinated; this was at a time many months before the myelination of the cortico-spinal decussation. This tract could not be confused with any part of the central tegmental tract or the median longitudinal bundle; nor does it correspond with any of the four parts of the reticulo-spinal tract described by Papez in the cat. Mettler and Mettler (1937) found the same decussation in a case of cyclopia and arhinia. And in a later communication, Marburg and Mettler (1943) showed a good photograph of this decussation in a second similar case; they also suggested that this decussation formed a part of the reticulo-spinal tract.

The first mention of tracing this tract by means of degeneration studies was made by Fusari (1896). In this case the lesion was a thrombosis due to syphilis. The Marchi technique could be used; but unfortunately his paper contains neither photographs nor drawings. From the description given, it is clear that the degeneration involved also the median longitudinal bundle, the central tegmental tract, and the cortico-spinal tract. As all these tracts descend near each other, it could not really be ascertained what was the contribution to the total degeneration made by the reticulo-spinal tract. Collier and Buzzard showed degeneration in the lateral reticulo-spinal tract in their third case. André Thomas (1903) reported a case of a hæmorrhagic lesion situated unilaterally in the pontine tegmentum. He showed that fibres arose from the reticular substance near the median raphe and descended into the anterior part of the cord; he called them the mesencephalo-spinal tract. In the case reported by Long and Roussy (1908), there was degeneration of a little tract lateral to the superior central reticular nucleus; the authors could not find the cells of origin; it may have been a reticulo-spinal tract. Papez' (1926) study of the reticulo-spinal tract in the cat remains the most important contribution to the anatomy of this tract. He recognized four components: ventral, lateral, medial, and crossed medial; of these the most extensive is the medial.

Cells of Origin

Man.—There is almost no evidence of the cells of origin in man. André Thomas found some fibres arising in cells near the median raphe in the pontine reticular substance. Foerster and Gagel (1932) searched for chromatolytic cells in the reticular substance in their cases of cordotomy, but could not find any.

Other species.—Papez (1926) showed that in the cat the lateral reticulo-spinal tract originates in a cluster of large cells medial to the masticator nucleus, the ventral reticulo-spinal tract comes from cells in the upper pons, cranial to the masticator nucleus and medial to the lateral lemniscus.

Cooper and Sherrington (1940), found, following cervical hemi-sections in the macaque, chromatolysis of cells of the reticular formation of the lower brain-stem and pons; they were more numerous on the contralateral side. "On the uncrossed side a group of them lay just dorsal to the medial part of the inferior olive"; some were dorsal to the medial lemniscus. "They were traceable as high as the locus caeruleus and nucleus masticatorius."

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Course

Man.—The course in man is inadequately known.

It appears that the medial tract joins the median longitudinal bundle. In association with this bundle, it enters the cord, running in the sulco-marginal region.

The lateral tract probably crosses the mid-line immediately, descending in the dorso-lateral part of the reticular substance. Collier and Buzzard reported in their third case degeneration of this tract in the position attributed to the rubro-spinal tract, dorso-lateral to the inferior olive. In the cord, the tract lies in the region of the lateral cortico-spinal and the rubro-spinal tracts.

The tract found by Pfeifer lay in the medial part of the reticular substance. It passed anteriorly as it descended, crossing the mid-line within the most caudal part of the region normally occupied by the cortico-spinal decussation. It ran in the anterior column of the cord.

Other species.—In the rabbit, Hashimoto (1928) found that most of the lateral reticulo-spinal tract is uncrossed. In the macaque, Bodian (1946) found that most of the total reticulo-spinal tract is uncrossed.

Tschermak (1898) investigated this tract in the cat. He found that the fibres which join the median longitudinal bundle run in a dorsal direction, and join the ventral and lateral parts of the bundle; some of these fibres then ascend and others descend into the bundle which borders the ventral fissure of the spinal cord. Tschermak described other fibres of the tract descending lateral to the median longitudinal bundle. As these fibres descend, they lie dorso-lateral to the inferior olive and medial to the spinal root of the fifth cranial nerve. In the cord they run in the dorso-lateral part of the cortico-spinal area, medial to the rubro-spinal tract. Probst (1899), who also worked on the cat, found that the fibres of the medial division pass through the mass of the ventral hypoglossal nucleus; they leave the median longitudinal bundle at the level of the cortico-spinal decussation, and come to lie anterior to the decussation. Papez, who also worked on the cat, described the ventral division of the tract as probably crossed. It runs posterior to the corpus trapezoideam and medial lemniscus, and lateral to the median longitudinal bundle. In the cord it is separated from the periphery by the vestibulo-spinal tract.

Warner (1952) found from his study of myelogenesis in the American water snake that the fibres of the reticulo-spinal tract that join the median longitudinal bundle come from both sides. Thus the medial division of the reticulo-spinal tract in this species is both crossed and uncrossed.

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Termination: Relation to Grey Matter

Man.—This is unknown.

Other species.—Tschermak (1898) in the cat found collaterals from that part of the tract that runs with the median longitudinal bundle running into the anterior horns of the spinal cord. Redlich (1899) who worked on the cat and dog found degenerating fibres from the ventral tract running into the anterior horns; he found some fibres ending round the cells of the medio-anterior angle of the horn. He found some of the fibres crossing the commissure to the opposite anterior horn.

Termination: Caudal Extent

Man.—This is unknown.

Other species.—Tschermak found that the uncrossed tract in the cat runs throughout the length of the cord. In the cat and dog, Redlich thought that most of the fibres of the reticulo-spinal tract run to the cervical and lumbar enlargement. Bodian (1946) found in the macaque that the reticulo-spinal tract descends at least as far as the mid-thoracic region.

Intermingling of Tracts

Man.—The medial reticulo-spinal tract is mingled with the median longitudinal bundle; and so in the cord it is mingled with the ventral cortico-spinal tract, the tecto-spinal tract, and the vestibulo-spinal tract. The lateral reticulo-spinal tract is probably mingled with the fibres of the lateral cortico-spinal tract, and with the fibres of the rubro-spinal tract, if this exists in man. Pfeifer's tract decussates within the decussation of the cortico-spinal tract, and it seems to continue along the cord with the other components of the sulco-marginal fasciculus.

Lamination and Arrangement of Fibres

Man.—These are unknown.

Other species.—Papez (1926) found that in the cat the more anterior fibres of the uncrossed medial division are the fibres that originate in the reticular cells of the pons, and the more posterior fibres are those that originate in the reticular formation of the medulla oblongata. Within the median longitudinal fasciculus, the medial tract lies lateral to the ascending and descending vestibular fibres.

Myelination, Size, and Number of Fibres

Man.—The fibres of the tract are large and myelinated. Pfeifer's tract is myelinated in the 36 cm. long embryo.

No fibre counts have been made in man.

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Other species.—Probst (1899) found in the cat that many of the fibres of the lateral reticulo-spinal tract are fine and myelinated.

Vestibulo-spinal Tract

The evidence for the existence of this tract in man is somewhat meagre, although it is better than that for the rubro-spinal tract. Collier and Buzzard showed degeneration in this tract in their third and fourth cases. Langworthy (1930) in his 29-week-old embryo showed a tract that in all probability was the vestibulo-spinal tract.

Von Monakow (1883) first showed that following a hemisection of the rabbit's cord in the cervical region there is atrophy of the lateral vestibular nucleus. The first full description of the tract was given by Held (1890) for the cat and the rat.

It used to be discussed at the end of the last century whether there was such a tract as a cerebello-spinal or whether the tract concerned was the vestibulo-spinal. A critical consideration of all the experimental evidence showed that the tracts thought to be cerebello-spinal were in fact vestibulo-spinal.

Cells of Origin

Man.—The only observations reported are those of Foerster and Gagel (1932). They found retrograde changes in the lateral vestibular nucleus in 2 cases of bilateral antero-lateral cordotomy.

Other species.—In the cat, Buchanan (1937) found that in addition to the lateral vestibular nucleus, the superior vestibular nucleus contributes to this tract.

Course

Man.—There is no adequate evidence of the course of this tract in man.

Other species.—Most workers consider that the tract is uncrossed. But Tilney and Casamajor (1924) described uncrossed and crossed portions of this tract in the kitten, which they called direct and crossed Deitero-spinal tracts. Hashimoto (1928) found that after performing hemisections on the cervical cord of the rabbit that there were changes in the lateral vestibular nucleus bilaterally, though they were predominantly ipsilateral. Buchanan (1937) found in the cat that the tract was entirely uncrossed.

As the axons leave the lateral vestibular nucleus, they pass anteriorly and medially, to lie dorso-medial to the facial nucleus and the nucleus ambiguus. They then lie lateral to the roots of the hypoglossal nerve, which separate them from the medial lemniscus. The tract then lies

dorso-medial to the superior olive and to the nucleus lateralis, where it is close to or mixed with the rubro-spinal tract. More caudally, it lies dorsal and lateral to the inferior olive. The tract here appears more compact, as it lies anterior to the spinal root of the fifth cranial nerve.

Held (1892) described this tract as running in the lateral column in the cat and rat; he stated that it lies here in man, but he backed this statement with no evidence. In 1894, Ferrier and Turner reported their investigation of this tract in an excellent paper, illustrated by good photographs; this paper stands out, as none of their contemporaries ever illustrated their work by anything but drawings, and many of the German workers omitted these. Ferrier and Turner found that in the macaque "The tract from Deiter's nucleus . . . was most distinctly seen in the upper cervical region, but could be followed into the lumbar enlargement. In the spinal cord it occupied the periphery of the anterior column from the anterior nerve roots to the median fissure along which it extended a short distance." Risien Russell (1897) stated that in the macaque and the dog, the tract in the cervical region does not extend as far medially as the median fissure; it occupies this position only in the lumbar cord.

The tract is traversed by the anterior roots. Lying medial to it is the tecto-spinal tract.

Termination: Relation to Grey Matter

Man.—This is unknown.

Other species.—Risien Russell (1895) working on dogs and monkeys, considered that a few fibres run to the grey matter of the opposite side; but reported later (1897) that the fibres "go to the grey matter of the anterior horn of the same side." Schäfer (1899) found after hemisections on the cord of the monkey that the fibres of the "tract of Löwenthal" pass into the anterior horn ipsilaterally, and that they "apparently terminate for the most part by arborizing amongst the anterior cornual cells"; the tract of Löwenthal consists of the vestibulo-spinal tract and other descending fibres of the anterior column. Schimert (1938) working on the cat, found that the vestibulo-spinal tract terminates near the anterior horn cells of the medial part of the horn; they were more easily seen in the cervical than the lumbar region.

Termination: Caudal Extent

Man.—According to Collier and Buzzard, the tract can be traced to the lumbar cord.

Other species.—Ferrier and Turner (1894) traced the tract in the

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macaque into the lumbar enlargement; and Langworthy (1929) found it in the newborn kitten running throughout the length of the cord.

Intermingling of Tracts

Man.—Too little is known about the course of the tract to relate it to other tracts.

Other species.—In the mammals in which this tract has been investigated, caudal to the olive it lies among the ascending fibres from the cord, spino-cerebellar, spino-tectal and spino-thalamic. In the cord, it is mingled with the tecto-spinal and median longitudinal bundle.

Myelination, Size and Number of Fibres

Man.—Langworthy found this tract already "heavily myelinated" in his 29-week-old embryo.

No fibre counts have been made in man.

Other species.—All workers describe this tract as made up of large myelinated fibres in mammals.

Olivo-spinal Tract

This tract, known in German as the Dreikantenbahn, was first described by Helweg, a Danish psychiatrist, in 1888. He did not differentiate the tract from the ventral bundle of the central tegmental tract; he thought that his tract was ascending, and that it conveyed the vasomotor fibres to the cerebral blood vessels. Von Bechterev (1894) took pains to record that he knew of the existence of this tract when he was studying histology in Flechsig's laboratory in 1884–1885. He stated that he had often demonstrated the tract to his colleagues in Kazan before Helweg described it, and that he had intended studying it in the newborn, but had been prevented from doing so, partly on account of his professional duties becoming too pressing, and partly because he had moved from Kazan to St. Petersburg to become professor. Apart from these domestic details, his paper shows that he was the first to insist that this is a descending tract, and to relate it to the olive. In the literature the tract is sometimes called olivo-spinal and sometimes spino-olivary. Von Bechterev (1899) pointed out that this is phylogenetically a very recent tract.

Cells of Origin

Man.—Returning to this tract in 1901, von Bechterev was able to show that it is intimately connected with the olive, most of its fibres originating in the inferior olivary nucleus. It is still unknown whether other nuclei make a contribution, and how much of the tract is spino-olivary and how much olivo-spinal.

Course

Man.—This tract, as soon as it leaves the olive, is situated anterior to the inferior olive, lateral to the roots of the twelfth nerve and lateral to the sulcus præolivaris medialis, which separates it from the cortico spinal tract; lateral to the tract is the ventro-medial part of the central tegmental tract. It is separated from the ascending fibres that constitute Gower's tract by the bulk of the inferior olive. Caudal to the olive, the tract lies medial to Gower's tract, although there is frequently some overlap between the two. Caudal to the decussation of the cortico-spinal tract, it lies on the periphery of the medulla oblongata and then of the cord. It is immediately lateral to the emerging anterior roots; often its medial part is traversed by them.

The tract varies in form on transverse section in different subjects and often on the two sides of the same subject. As von Bechterev pointed out, the description "triangular" is apt only in the middle of the cervical cord; further caudally, it has the form of a meniscus.

Termination: Relation to Grey Matter

Man.—Thalbitzer (1910) came to the surprising and old-fashioned conclusion that the fibres of this tract join the anterior roots as they leave the white matter of the cord; he was certain that he could find no evidence that the fibres go into the anterior horns. Schwartz (1916) found that near its termination the fibres turn laterally; but some also turn medially and some were seen to enter the adjacent grey matter.

Termination: Caudal Extent

Man.—The bulk of evidence shows that this tract does not descend caudal to the fourth or fifth cervical segments. Obersteiner (1900) wrote that the tract is rarely found below the sixth cervical segment; but in 1901 he published a case showing the tract descending into the thoracic cord; the lesion in this case was so large that it involved not only the olive, but also most of the medulla oblongata; and so other tracts must have degenerated besides the olivo-spinal. In the case reported by Kattwinkel and Neumayer (1907) the tract could be traced to the fourth thoracic segment.

It is not yet known what proportion of the fibres of Helweg's tract are spino-olivary and what are olivo-spinal. The total tract, caudal to the olive, is often mingled with the ascending fibres of Gower's tract.

Myelination, Size and Number of Fibres

Man.—Von Bechterev (1899) and Schwartz (1916) found that this tract myelinates later than the cortico-spinal tract.

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The fibres of this tract are very fine; Helweg stated that they measure 1·5 to 2 μ.

No fibre counts have been done in man.

Central Tegmental Tract

The central tegmental tract was first described and named by von Bechterev in 1885; he found it in the human embryo. It was never suggested that this tract or any part of it ran into the spinal cord, until Weisschedel reported his study of the tract in 1937, which was carried out on normal human brains. Weisschedel claimed that at the middle of the pons the tract divides into three: a ventral, a dorsal, and a medial bundle; and he found that the medial bundle continues down into the spinal cord. This view has not so far been confirmed; before it can be considered, such fibres would have to be shown in degeneration studies. Ogawa (1939) did not find such a component in the cat; he considered that Weisschedel's medial bundle was not a part of the central tegmental tract. Verhaart (1949) searched for such spinal fibres in two human cases where there was degeneration of this tract; but he found none. He mentioned no spinal component of this tract in the 24 macaques in which he had made lesions so as to cause degeneration in the central tegmental tract.

Periaqueductal Tract

In 1891, Schütz described in man a tract running in the floor of the fourth ventricle and the aqueduct, throughout the medulla oblongata, pons and mid-brain. One is astounded to note that he named this tract the "Dorsale Längsbündel," which was translated into Latin as fasciculus longitudinalis dorsalis; Schütz was thoroughly familiar with what was called in German the "Hintere Längsbündel"; at the time the usual Latin name for this tract was fasciculus longitudinalis posterior. As "posterior" and "dorsalis" are interchangeable, it is apparent that Schütz gave to his new tract the name already given to another tract; and to add to the confusion, the two tracts keep a close relation one to another throughout their course. Schütz's tract has also been called the fasciculus longitudinalis substantiæ griseæ centralis, the fasciculus periaqueductalis, the fasciculus tegmentalis dorsalis, fibræ substantiæ griseæ centralis, tractus peri-ependymalis longitudinalis and the diencephalic periventricular system. The name periaqueductal tract is chosen here; for the direction of conduction, the origin and termination are complicated and insufficiently known, and the name is short.

Krieg (1932) studied this tract in normal albino rats' brains. He did not find any part of this tract descending into the spinal cord.

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Krücke in 1949 described in man a "fasciculus para-ependymalis," situated lateral to the central canal. It is a small fine bundle of mixed myelinated and unmyelinated fibres. Krücke did not ascertain whether it was an ascending or a descending tract. This may be the continuation of Schütz's tract. Krücke named his tract the para-ependymal tract, and Schütz's tract, the peri-ependymal tract.

Actually, these fibres described by Krücke had already been noticed in man by Rothfeld in 1912.

Cells of Origin

Man.—Schütz (1891) described connexions beween this tract and the following structures, but it is unknown whether the axons originate or terminate in them: the periventricular grey of the epithalamus, the dorsal thalamus, the corpus subthalamicum, the nucleus of Darkschewitsch, the posterior commissure, the habenular commissure, the nuclei of all cranial nerves, except the first and second, the reticular substance, the corpora quadrigemina, the anterior horn cells of the cord, and probably the red nucleus. None of this can be regarded as known, as it has never been confirmed.

Other species.—Beattie, Brow, and Long (1930) found in the cat that some axons originating in the posterior part of the hypothalamus, medial to the fornix, and mammillo-thalamic tract, run into this tract. Krieg gives the following as the origin of this tract: a division of the cortico-thalamic tract descending through the medial fore-brain bundle, other fibres of the medial fore-brain bundle, fibres from the region of the reticular nucleus of the thalamus and zona incerta, fibres from the ventral thalamic nuclei of the mid-line, chiefly the nucleus reuniens; from the hypothalamus the axons come from the suprachiasmatic nucleus, the posterior nucleus, the ventro-medial and dorso-medial nuclei, the arcuate nucleus, and probably the premammillary nuclei. According to Kappers, Huber, and Crosby (1936) (the latter two authors worked on this system) the tract in mammals starts in the dorsal tegmental nucleus.

Course

Man.—The tract runs in the central grey matter, immediately adjacent and ventral to the aqueduct, and dorsal to the cranial nerve nuclei. In the more cranial part of the medulla, it stretches from the mid-line beneath the whole of the floor and round the lateral walls of the fourth ventricle.

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Termination

Man.—It is not yet known whether its connexions are its origins or its terminations. The tract is largest in its most cranial part.

Other species.—Krieg (1932) found that in the rat the tract divided into ventral and dorsal divisions at the level of the posterior commissure. He could not trace the dorsal division below the mid-brain nor the ventral division below the dorsal motor nucleus of the vagus. Crosby and Woodburne (1940) studied the tract in birds; they too could not trace it below the vagus.

Intermingling of Tracts

Man.—This tract runs isolated in the grey matter.

Myelination, Size, and Number of Fibres

Man.—This tract is not myelinated at birth. According to Krücke (1949) it myelinates during the first year of life. They are very fine fibres.

No fibre counts have been made in man.

Other species.—According to Schütz (1891), the tract cannot be seen in 10-day-old, but it can be in 1-month-old kittens.

Hypothalamo-spinal Tract

This tract has been described only in the cat. It seems likely that it also exists in man, as it has to do with hypothalamic control of the sympathetic system of the thoracic and upper lumbar cord. But there is no mention of it in man in the literature. The account that follows is that of Beattie, Brow, and Long (1930), who described the tract.

Cells of Origin

Cat.—The cells of origin are situated in the caudal part of the hypothalamus, medial to the fornix and to the mammillo-thalamic tract.

Course

Cat.—The tract is mostly, but not entirely, uncrossed. The fibres "descend alongside the lateral and ventral boundaries of the central grey matter of the mid-brain, and eventually become concentrated into the more ventral part of the posterior longitudinal bundle and the dorsal part of the reticular formation of the medulla." Caudal to the decussation of the pyramids, the fibres lie near the vestibulo-spinal tract.

Termination: Relation to Grey Matter

Cat.—The fibres of this tract end in the "intermedio-lateral column of grey matter."

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Termination: Caudal Extent

Cat.—The fibres run to the thoracic and the upper lumbar parts of the cord.

After collecting this material from the literature, we are left with the impression that material providing information on anatomical facts must come into the hands of neurologists every day, and that such material is wasted. For the custom of studying patients during life and following histologically the degenerated fibres after death seems to have passed into oblivion. Whatever the causes of this change in fashion are, one of them is not that knowledge of the anatomy of the long descending tracts in man is now complete.

In the following table, summary of the main points of the anatomy of these tracts in man is shown. The sign + indicates that the point tabulated is known, the sign − that it is unknown, and the sign ± that it is unverified. We would once again like to emphasize that the table refers only to man.

LONG DESCENDING TRACTS IN MAN

	Cortico-spinal tract	*Median longitudinal bundle*	*Tecto-spinal tract*	*Rubro-spinal tract*	*Reticulo-spinal tract*	*Vestibulo-spinal tract*	*Olivo-spinal tract*	*Central tegmental tract*	*Periaqueductal tract*	*Hypothalamo-spinal tract*
Cell of origin	±	±	−	±	−	+	+	±	−	−
Course	+	+	+	−	±	+	+	−	±	−
Termination: related to grey matter	+	−	−	−	−	−	−	−	−	−
Termination: related to caudal extent	+	−	−	−	−	−	+	−	−	−
Size of fibres	+	±	±	−	±	±	±	−	±	−
Topographical arrangement	±	±	−	−	−	−	−	−	−	−
Myelination	+	+	±	−	−	−	−	−	±	−

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MEMORY: THE ANALOGY WITH FERROMAGNETIC HYSTERESIS

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THE neural basis of a memory trace or engram is unknown. Each of the few suggestions that have been made is apparently in conflict with some part of the experimental evidence. This paper describes a new explanation, which arises without further assumptions from the co-operative theory of neuronal organization (Cragg and Temperley, 1954). It is that a co-operative assembly of neurones would exhibit hysteresis, as in ferromagnetism. It can be shown experimentally that this property enables a co-operative assembly to give a conditioned response, and that the engram is distributed throughout the assembly. This hypothesis seems to be compatible with the present experimental evidence, and it suggests further tests. A synopsis of the co-operative theory is given below.

(1) PROPERTIES OF THE ENGRAM

A. Localization

In mammals the engram is stored in the cerebral cortex. In a decorticated animal there may be some slow conditioning in subcortical structures, but it is doubtful whether this occurs in the intact animal (Lashley, 1950, section 5). Within the cerebral cortex the engram is widely distributed. To prevent an animal from performing a simple conditioned reflex learnt visually, extirpation of the primary visual area of the cortex has to be almost complete: Lashley (1935) found that rats could retain habits based on the discrimination of light intensities when any small region of the striate cortex was left intact, and that rats could discriminate visual figures with a remnant of only one-sixtieth part of the striate cortex (Lashley, 1939). If extirpation is incomplete, the performance of the animal does not depend on where in the visual cortex the remnant is situated. Moreover, lesions in the motor area, in association areas, and in other sensory areas cause little deficit in the

performance of learned responses. What deficit there is increases with the volume of cortex destroyed, and with the complexity of the conditioning situation (Lashley, 1950, section 7).

B. Spatial Organization

Although the engram is widely distributed in the cortex, no particular long range tract of axons through the cortex is essential to the retention of the engram. Thus Lashley (1944) showed that in rats a variety of bilaterally symmetrical cortical incisions, each half as long as a cerebral hemisphere, interfered with neither the learning nor the retention of a maze habit. Similarly, the removal of a band of cortex surrounding the primary visual area in monkeys caused no detectable loss of visual memories. Long range conduction is not essential in the afferent and efferent tracts either, for Ingebritsen (1933) has shown that hemisection of the spinal cord of rats at the second cervical level together with section of the other half of the cord at the fifth cervical level did not interfere with the retention of a maze habit nor with the learning of a latch-box habit. Further remarkable experimental results of this kind, including the surprising absence of deficiency in Man after severance of the corpus callosum, are reviewed by Lashley (1950, section 3).

C. Time Relations

The memory trace of a simple situation may be established instantly or at the first encounter, not only in Man but also in the smaller mammals and in octopus (Boycott and Young, 1950). More complex traces are established more slowly, the proportion of mistakes falling gradually with the number of presentations. Lesions, if sufficiently large, increase the time needed to attain a given proficiency. The amnesia produced by an extensive lesion may result from reduced "vigilance," or reduced "ease of recall," rather than from destruction of the memory trace (Lashley, 1950, sections 7 and 8). In the octopus, the removal of a particular lobe leaves the animal able to retain a memory trace for only a few minutes at a time (Young, 1951).

D. Stability

Surgical anæsthesia does not interfere with a memory trace. It is said that convulsions, ischæmia and concussion seldom cause more than a temporary reversible amnesia, though this view appears to be a matter of general inference rather than a result of critical experiments (*see* Konorski, 1948, p. 99; Hebb, 1949, p. 13; Eccles, 1953, p. 219). Russell (1949) has shown that the deficit produced in rats by a series of electroshock convulsions depends upon the difficulty of the maze-habit learned.

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The inhibition of a conditioned reflex does not involve the loss of the memory trace (Konorski, 1948, p. 9).

In summary, the properties of the engram can be expressed in two paradoxes, one spatial, the other temporal: the engram is distributed throughout the cortex, yet is not dependent on direct connexions between distant cortical areas; the engram can be established very rapidly, and yet can endure gross changes in the physiological state of the cortex.

(2) Theories of the Engram

A. Association of Cortical Centres

This theory may be stated as follows: the conditioned and the unconditioned stimuli each influence, and are represented by, a group of neurones called a "cortical centre"; learning consists of the formation of some kind of functional connexion between the cortical centres representing the two stimuli (*see* for example Konorski, 1948, pp. 8 and 87).

A hypothesis of this kind conflicts with the evidence on the spatial distribution of the engram. Moreover, it does not show how a connexion between the cortical centres can be formed taking into account the known temporal properties of the engram.

B. Persistent Excitation

Circuits or chains of neurones are supposed to exist within the cortex which are set into oscillation when the conditioned and unconditioned stimuli are presented together; the oscillatory activity persists, and represents the association between the two stimuli (*see* for example Ebbecke, 1919; Edgell, 1924; Young, 1938; Lashley, 1942; Konorski, 1948, p. 88; 1950, p. 426; Hebb, 1949; Eccles, 1953, p. 217).

This hypothesis implies that the engram is due to the activity of certain neurones, and not all neurones. The engram has therefore a spatial localization, even if the neurones concerned are scattered throughout the cortex. This result is difficult to reconcile with the indifference of the engram to cortical incisions. If the neurones concerned are not scattered, there is conflict with the evidence on the localization of the engram. The hypothesis shows how an engram could be formed quickly, but does not explain how it endures changing physiological conditions.

C. Synaptic Facilitation

The theory is that the joint presentation of the conditioned and unconditioned stimuli sets up activity in circuits or assemblies of neurones;

the synapses involved in this activity become facilitated, possibly by minute anatomical changes; a similar pattern of activity is then more easily set up in these neurones, and with sufficient joint presentations of the stimuli the conditioned stimulus alone becomes effective in eliciting the response. Thus neuronal circuits become resonant (instead of oscillatory, as in the previous section), and this resonance represents the engram, and may be rendered stable by anatomical alterations (discussions of this hypothesis are given by authors cited in the previous section.

This form of hypothesis is subject to the same criticisms of spatial arrangement as the previous one. It does, however, provide a possible explanation of the stability of the engram.

(3) Synopsis of the Co-operative Theory

This theory is based on the physical principle that assemblies containing large numbers of atoms with a high degree of mutual interaction behave in a manner that is qualitatively quite different from that of assemblies with less interaction. An example is the co-operative phenomenon of ferromagnetism which arises specifically from the *interaction* of atoms that would not otherwise be ferromagnetic. When a substance is cooled from just above to just below the Curie temperature at which it becomes ferromagnetic, the magnetic properties of the substance change qualitatively, although the individual properties of the atoms have been little affected by the small change of temperature. Above the Curie temperature the magnetic moments of neighbouring atoms can point in different directions, and the average magnetization of the substance is zero in the absence of a magnetic field impressed from outside. Below the Curie temperature the interaction between the atoms exceeds a certain critical level, and large blocks of neighbouring atoms lose their individual freedom of orientation and take up the same orientation so that a nett magnetization can exist in the absence of an external field. These blocks of orientations are called "domains" and the atoms of a ferromagnetic body are arranged in an intricate pattern of domains of differing orientation so that the total free energy, of the assembly is as low as possible. A change of external magnetic field disturbs the domain pattern which reforms in a new pattern of minimal free energy, for the domains are free to move through the assembly, the atoms changing their orientation but not their position. This requirement for equilibrium that the over-all free energy of the domain pattern should be minimal imposes a wholly new organization on all the atoms of the assembly as soon as the assembly becomes co-operative.

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The conditions for co-operative phenomena to occur in an assembly are that each member of the assembly should be able to exist in two or more different energetic states and that the interaction between members should exceed a certain critical level defined as follows: let $p=e^{U/kT}$ where U is the difference in energy between a pair of like and a pair of unlike neighbours, T is the absolute temperature, and k is Boltzman's constant, and let z be the number of members of the assembly which interact with any one member; then if p^z is of the order 10 or more the assembly will become co-operative and domains will be formed. It can be shown that when an atom makes a transition between two energetic states, the probability that this transition will favour similar transitions among the atom's neighbours divided by the probability that it will inhibit similar transitions is equal to the quantity p defined above. The condition for co-operative phenomena to occur, $p^z > 10$, thus involves a property of the individual members of the assembly (p, the relative frequency of stimulatory and inhibitory interactions) and a property of the assembly as a whole (z, the connectivity, or number of members interacting with any one).

In the central nervous system large numbers of neurones occur closely packed together. Each cell-body gives rise to axons and dendrites which intermingle with the neighbouring neurones. It is conceivable that there is sufficient interaction for co-operative processes to occur if neurones fulfil the conditions set out above. First it would be necessary for neurones to be able to exist in two or more different energetic states. The presence or absence of an action-potential clearly provides two different states and there are many other possible states of inhibition or sub-liminal excitation. Secondly the interaction between the neurones must reach the critical level. By interaction is meant the change in the membrane potential of one neurone caused by a change in the membrane potential of another, whether by the activation of synapses or by extracellular current flow, or both. The critical level of interaction depends on the relative frequency (p) of excitatory and inhibitory interactions, which can hardly be estimated at present, and upon the connectivity (z) which can be estimated from histological measurements. In the cerebral cortex of cats the cell-bodies range in diameter from 10–20 μ, the separation of the centres of neighbouring cell-bodies ranges from 20–25μ, and the dendrites extend 250–500 μ away from the cell-body (Sholl, 1953). This means that some thousands of cell-bodies lie within the dendritic tree of a given neurone. Over half the neurones in this cortex have main or collateral axons ramifying within the cortex and the length of these intracortical axons is comparable with the radius of the dendritic

trees of their cell-bodies. The collateral axons of the neurone are thus able to come into contact with the dendrites of thousands of neighbouring neurones (*see* Sholl, 1954).

With a conservative value of 1,000 for z it turns out that the conditions $p^z > 10$ necessitates $p > 1{\cdot}002$, so that the number of excitatory interactions needs to exceed the number of inhibitory interactions by only 0·2 per cent for co-operative processes to occur. It is therefore much more likely that neurones are organized in an overall domain pattern of minimal free-energy than that they are individually free to conduct impulses or not like the relays of a telephone exchange. Assuming for the moment that neurones do form a domain pattern one would expect by analogy with ferromagnetism that all the neurones in a domain would have the same membrane potential which might be different from the resting potential. This would correspond to a maintained state of excitation or inhibition in the domain, though not in the individual neurones since the domains are free to move through the assembly of neurones seeking the pattern of minimal free energy. Impulses arriving in sensory cortical areas would promote the formation there of domains of excitation which might later move over a motor area and elicit a muscular response.

From the hypothesis that neurones are organized co-operatively it has been possible to make six deductions which seem to be in better agreement with biological observations than the results of other hypotheses (Cragg and Temperley, 1954). The present paper describes a further deduction from the hypothesis: neuronal assemblies should exhibit hysteresis as in ferromagnetism and this property would enable them to store engrams in a manner consistent with the biological results summarized above.

(4) The Engram as a State of Hysteresis

The main point of this hypothesis is that memory is due to the hysteresis of an assembly of neurones, but does not entail changes in the properties of any individual neurones. Any subdivision of the assembly large enough to accommodate a reasonable number of domains possesses the property that is the engram to the same extent (per unit volume) as the whole assembly.

Hysteresis is a certain kind of relationship between an external constraint applied to a co-operative assembly and the corresponding property of the assembly. An example is the relationship between an external magnetic field applied to a ferromagnetic substance and the magnetization of the substance. The relationship is roughly analogous

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to the mechanical effect known as "back-lash" : a change in the external magnetic field causes a change in the magnetization of the substance, but this is not completely annulled when the field is brought back to its original value. The state of magnetization of a ferromagnetic substance depends not only on the existing applied magnetic field but also on the previous history of magnetization.

When an increasing magnetic field is applied to a ferromagnetic substance, the domains magnetized in the direction of the applied field grow at the expense of domains of opposing magnetization. If the external field increases sufficiently the domain pattern becomes unstable, and discontinuous reorientations of some domains occur. When the external field is reduced again, these reorientations are not reversible at the field strength which produced them. This is because the energy of the assembly depends secondarily upon the mechanical stresses set up by magnetization. The pattern of domains is determined by all the previous magnetic changes that the substance has experienced as well as by the present applied magnetic field : (for accounts of ferromagnetic hysteresis *see* Becker and Döring (1939), Stoner (1934), and for domain patterns *see* Stewart (1954) and Corner (1953)).

It is well known that hysteresis causes the dissipation of energy as heat when the magnetization is changed cyclically as in a transformer. Such dissipation of energy invariably accompanies hysteresis, and arises from secondary effects (such as the magneto-mechanical stress mentioned above) rather than from the primary co-operative property of the assembly. Secondary effects which dissipate energy are, however, inevitable in a neuronal assembly, for an electric current must flow (intra- or extra-cellularly) between neurones in domains of different membrane potentials. It is therefore a reasonable hypothesis that the neuronal domain pattern will respond with hysteresis to afferent impulses arising from external stimulation. Thus the domain pattern at any instant will depend upon the afferent impulses received in the past, as well as upon those currently arriving.

In applying the analogy of ferromagnetic hysteresis to cortical neurones, it must be emphasized that it is the detailed arrangement of the domain pattern rather than the total magnetization which is of biological significance. In a specimen of ferromagnetic material, many different domain patterns could give the same total magnetization. In an assembly of cortical neurones, the detailed arrangement of the domain pattern will determine which neurones fire efferent impulses, and also what change of domain pattern is produced by an impulse arriving in a given afferent axon. The detailed domain pattern in a

piece of iron is dependent on every magnetic influence that the iron has experienced since it first became ferromagnetic. Domain patterns may be very complex (*see* for example the pattern reproduced in fig. 1), and

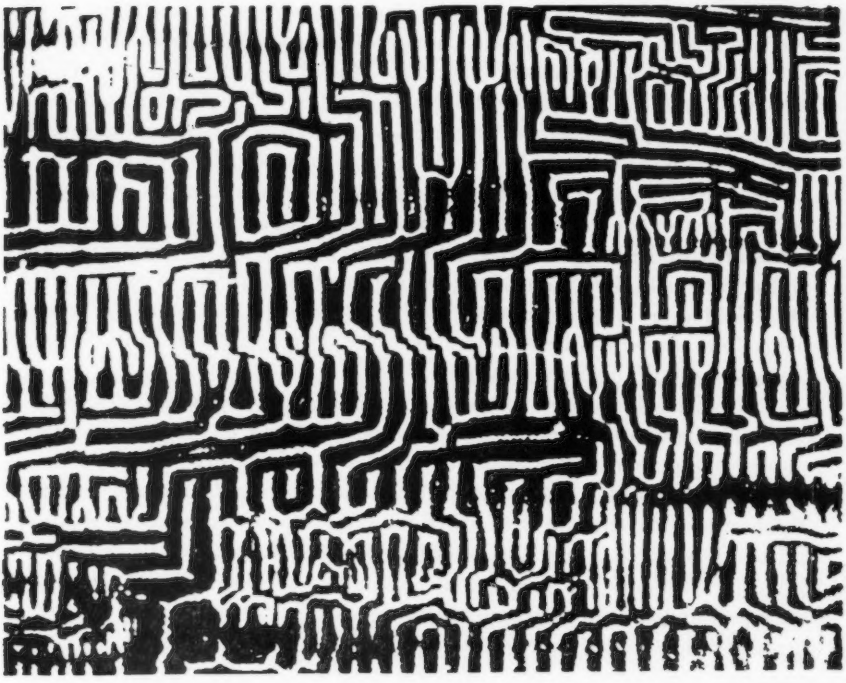

FIG. 1.—An example of a domain pattern on a mechanically polished surface. (Photograph by H. J. Williams reproduced by courtesy of *The Physical Review*.)

large numbers of domain patterns are possible within a given assembly of atoms. In this sense a piece of iron has a memory of immense capacity. The domain pattern in an assembly of cortical neurones should similarly be able to store large numbers of engrams. Just how many depends on the size of the domains, the amplitude of the random fluctuations in the membrane potentials of the neurones, and on the degree of correlation between the voltage of one domain and its neighbour. These factors are at present difficult to estimate, and it may be more useful to describe next a demonstration of a simple conditioned response due to the hysteresis of a piece of iron, and to show that this process is compatible with the properties of the cortical engram summarized above.

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(5) Demonstration of a Conditioned Response in Iron

The stimuli applied to the iron are magnetic fields, and the response is a change of total magnetization (the detailed changes in the domain pattern are not detected, and only one engram will be established). A magnetic field which increases from zero to some steady value and then declines again to zero causes a change of magnetization and this may be called the unconditioned response. An alternating magnetic field which is gradually attenuated to zero leaves the iron unmagnetized (the domains are in a pattern of minimal free energy, and their magnetic moments cancel). If therefore the alternating field is applied to an unmagnetized body it causes no change of magnetization (no response) and can be used as the conditioned stimulus. When the D.C. and A.C. fields are applied together (the stimuli are associated) the iron reaches and retains a higher state of magnetization than was produced by the D.C. field alone (the engram is stored). A later application of the A.C. field alone (the conditioned stimulus) then decreases the magnetization (causes a conditioned response).

The successive cycles of the A.C. field cause decreasing amounts of demagnetization (conditioned responses). Thus the repeated application of the conditioned stimulus without reinforcement with the unconditioned stimulus leads to the extinction of the conditioned response. To show that the engram is stored in the iron, and not in the magnetizing coils or associated circuits, a conditioned piece of iron may be removed from the coils and replaced by an unmagnetized piece. There is then the usual unconditioned response, but no conditioned response. When the first piece of conditioned iron is returned to the coils, the conditioned response reappears. To show that the engram is distributed throughout the iron, a bundle of iron rods may be conditioned and removed from the coils. Each one, when replaced, will then give the conditioned response.

A practical arrangement for demonstrating these results is illustrated in fig. 2. Iron rods stand inside a pile of four concentric coils (the focusing coils of cathode ray tubes are suitable) which apply the magnetic fields and detect the change of magnetization. The latter appears as a decaying (but not alternating) potential, and may be used to modulate the rate of firing of a thyratron connected to a loud speaker. The response then consists of a sequence of loud clicks, declining in repetition rate, and similar to those produced by a train of impulses in a peripheral nerve. To prevent the alternating magnetic field from activating the response system, two opposed search coils are used and balanced by a potentiometer with respect to the A.C. field. The rods used must show a marked hysteresis cycle, and must not be demagnetized

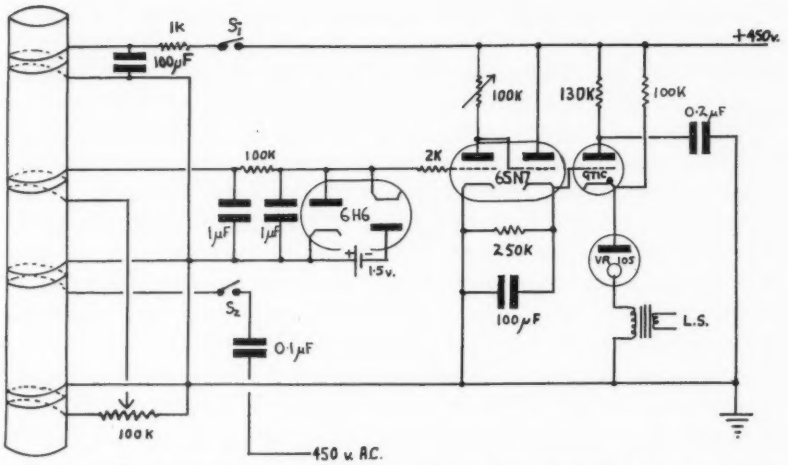

FIG. 2.—The circuit of a practical arrangement for demonstrating a conditioned response in iron. S_1 is the Unconditioned Stimulus key, S_2 Conditioned Stimulus. The coils have 23,000 turns each.

by mechanical shock when withdrawn from the coils. A bundle of mild steel rods consisting of the uprights of clamp stands has been found suitable.

(6) Suggestions for Experimental Tests

A. *The Electrical Detection of the Learning Process*

A more detailed consideration of the changes of domain pattern during the learning of a simple conditioned response suggests that the learning process should be detectable in electrical recordings from cortex under appropriate conditions. Our theory is that a stimulus S_1 provokes a set of afferent impulses in the axons entering a sensory area, and thereby changes the domain pattern locally towards excitation. The total domain pattern is then out of equilibrium and follows a course of change A which restores equilibrium by reducing the total free energy of the domain pattern as far as possible, with the minimal flow of current between domains. This course A does not necessarily involve any output (response). During the course A a second stimulus S_2 raises the excitation level of domains in the same or in a neighbouring sensory area. If S_2 had been presented alone, a course of domain pattern change B would have been followed, leading to an unconditioned response R. When S_2 is presented after S_1, the course of domain pattern neutralization changes from A to B', where B' is similar to B and also leads to the response R, and the re-establishment of equilibrium with minimal current flow.

With repetitions of the S_1 S_2 sequence, the hysteresis of the domain pattern causes a course of domain pattern neutralization B'' (similar to B') to be adopted earlier and earlier, even before S_2 has arrived, in order to reduce the time during which the domain pattern is out of equilibrium, and therefore the amount of current flowing between domains. This is the fact of learning, for when S_1 is presented alone, the course B'' leading to the response R is adopted before S_2 is due, so that if S_2 is omitted a response is still obtained. The change of course of domain neutralization (A+B′←B″) has "inertia" in that several repetitions of the S_1 S_2 sequence are needed to cause B'' to be adopted before S_2 is due, and also "momentum" in that if S_2 ceases to follow S_1, the course A is only gradually re-adopted.

The essential point of this analysis is that learning should be detectable as an earlier and earlier return to equilibrium after the presentation of S_1 and S_2. Suppose for example that in Burns' (1951) preparation of isolated and unanæsthetized cerebral cortex the stimuli S_1 and S_2 were applied as electrical shocks to the surface of the cortex. S_1 will set up the long (4 seconds) positive response, with superimposed oscillations, which represents the period of dis-equilibrium and raised potential energy during which the domains travel round the area (producing the oscillations) to reform their pattern of minimal free energy. If S_2 is applied immediately this response from S_1 has finished, another long response will follow (Burns, 1951) making say 8 seconds in all. If now S_1 and S_2 are presented in this manner repeatedly, learning would show itself as a reduction in the total duration of the response to say 6 seconds (i.e. the time needed to restore equilibrium is reduced by adopting the new course B'' of domain pattern change). If S_1 were then presented alone, a response lasting about 6 seconds should be evoked, but repetitions of S_1 alone should lead to a return to the earlier 4 seconds response. It is, however, possible that thalamic connexions are necessary for learning to occur, in which case the isolation of the cortex would have to be omitted. If the learning process could be detected electrically, much more accurate timing of the process would be possible than in the usual whole animal experiments.

B. *The Test of a Possible Secondary Learning Process*

Hysteresis of a domain pattern could only provide a mechanism for immediate memory, and as with the other hypotheses discussed above, some more permanent secondary process is required to explain the stability of the engram. Whether or not such a process exists can be tested by a simple experiment which measures the deficit in a learned

response produced by anæsthesia or electroshock as a function of the time interval between the conditioning and the treatment. This could be done with the usual experimental animals or with human psychiatric patients receiving ECT treatment. A simple task that can be learnt quickly with a small number of presentations should be used. Once a suitable proficiency has been attained, a treatment calculated to disrupt the established domain pattern (e.g. anæsthesia or electroshock) may be applied after a definite time interval. The subjects can be tested at a fixed time interval after the conclusion of the original conditioning sufficient to allow complete recovery from the intervening treatment. A deficiency which increases as the time interval between the end of the conditioning and the disrupting treatment decreases would indicate the time course of a secondary learning process. Such a result would be compatible with the rather vague experience of loss of immediate memory after concussion in Man.

(6) Discussion

If the memory trace is stored by the hysteresis of a domain pattern the difficulties of the previous theories with spatial organization do not arise. The hypothesis has also the advantages of the co-operative analogy: first that no more detailed geometrical arrangements of neurones are required for the cortex to function than would be provided mechanically during growth; secondly that the hypothesis is founded on the observed anatomy of neurones, that it takes into account the immense overlapping and interaction of neurones, and that it does not postulate improbable discrete circuits of neurones. The hypothesis proposed in this paper is a possible explanation of immediate memory, provided that a more stable secondary formation of the engram can be shown to occur.

Acknowledgments

We are indebted to Professor J. Z. Young, Mr. B. B. Boycott and other colleagues for helpful criticisms.

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NOTICES OF RECENT PUBLICATIONS

DISORDERS OF THE CEREBRAL VESSELS

Cerebrovascular Disease. By JAMES PETER MURPHY, M.D. The Year Book Publishers, Inc., Chicago. 1954. Pp. 408, 128 figs. £4 10s.

That a book on cerebrovascular disease should be written by a neuro-surgeon would have been surprising twenty-five years ago, but the surgical treatment of intracranial aneurysms and angiomas is now well established, and the operative evacuation of massive clots resulting from intracerebral hæmorrhage of the ordinary kind has proved its value in certain cases. These subjects are well covered in the present volume: the author is writing from his own experience, and the relevant literature is presented in its true perspective. But even in these chapters, which are the best, the reader will find himself occasionally halted by a dogmatic statement which without qualification is misleading. To take a single example, it is stated that true hæmangio-blastomas are uncommon intracranial tumours. Yet in Jefferson's Manchester series there were 74 of these growths among 635 posterior fossa tumours, being the fourth largest group. The anatomical sections of the book are clearly presented with appropriate diagrams, though it is disappointing to find no reference to the classical work of Abbie in an otherwise full account of the cerebral arteries. The physiological aspects of the subject are dealt with at some length with reference to the recent work of Kety and Schmidt, but the discussion is biased by the author's surgical beliefs, as for example that if the posterior cerebral artery is filled by a carotid arteriogram this indicates the route followed by the blood stream under normal conditions. A comparable statement is that if both anterior cerebral arteries fill from an injection into one carotid this usually means that the blood flow comes from one carotid trunk. These interpretations neglect the pressure of the injections, a source of error demonstrated by the experiments of Macdonald and Potter, whose work is not mentioned. That stellate block is being used all over the world in the treatment of hemiplegia due to cerebral embolism or infarction may or may not be the fact as claimed by the author, but even if true this statement will not convince physiologists of the correctness of his theories concerning cerebral vasospasm. These are perhaps minor blemishes in a book which covers a great deal of ground and is for the most part up to date as, for example, in the description of collagenous vascular disease. More serious is the lack of respect paid to the methods of clinical neurology. When we are told that temperature conduction is readily evaluated with a piece of ice, and deep sensibility with firm pressure and by the application of a tuning fork with vigorous vibrations to bony prominences, with no addition or qualification, and find this only one instance of a number of inadequate directions to the student, we cannot but feel that the book would have been better done by a neurologist and surgeon in collaboration.

The production is of good quality, and the illustrations well chosen and presented. There is a bibliography at the end of each chapter. The book is to be commended as a useful work of reference for the critical reader.

C. P. SYMONDS.

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Malformations et Tumeurs Vasculaires du Cerveau. By ROGER PLUVINAGE, 1954. Pp. 323. Masson et Cie, Paris. Price 3,000 fr.

This monograph comprises sections on intracranial aneurysms, angiomas, Sturge-Weber disease, telangiectases, cavernous angiomas and the syndromes of the hæmangio-blastomas, including those occurring within the spinal canal. For each condition there is a careful anatomical, histopathological and clinical description, and the opinions expressed, supported by an extensive bibliography are those generally known and in the main accepted, at the present time. Nearly half the book is devoted to aneurysms, and their description includes those in rare situations. However, as the author states in the preface, the monograph is not intended as a complete and comprehensive study and some aspects are dealt with only in general terms, this being particularly evident with regard to aneurysms, for the burning topic of the present time, that of treatment, is dealt with superficially and few surgical statistics are given.

The book is well produced with a large number of X-ray reproductions and illustrations and will commend itself as an up-to-date work of reference on this increasingly important group of intracranial anomalies.

VALENTINE LOGUE.

DISSEMINATED SCLEROSIS

Multiple Sclerosis. By D. MCALPINE, N. D. COMPSTON and C. E. LUMSDEN. 310 pages. 115 illustrations. E. and S. Livingstone Ltd. 1955. 35s.

It is remarkable that this book is the first in this country to provide a comprehensive survey of multiple sclerosis, one of the commonest as it is amongst the most baffling and interesting of nervous diseases. It is more than fortunate that Dr. McAlpine's long dedication to this task should have resulted in a work so thorough, so informative and so stimulating. No physician could read it without feeling the fascination of the problems set by this disease or fail to feel the authors' urge towards their clarification and their determination to probe as far as is yet possible into the many questions which remain unanswered. While the difficulties are not ignored and there are no striking advances to record, one derives from reading it a feeling of hopefulness, a conviction that though the future will be difficult it is not too dark, which is in pleasing contrast to the gloom which now everywhere pervades neurological teaching and practice on this disease.

Treatment of the subject is global and it seems unlikely that any current question on any aspect has been omitted. Several chapters deal with the natural history of the disease; familial and geographical incidence is discussed, and ætiological factors are analysed and appraised. Symptomatology, especially in the early stages, when diagnosis is so often difficult and yet essential if treatment is ever to be of real value, is described with many adequate case histories illustrating modes of onset and course, and this is supplemented by a most valuable chapter on differential diagnosis. Here there is not only the usual comparison of clinical syndromes but the significance of individual symptoms and signs is discussed in detail.

In the chapter on treatment general management of the patient is given its important place and the various methods of drug and hormone therapy are described though it is clear that none of these appear to the authors to be of outstanding efficacy. Symptomatic treatment, rehabilitation and other matters receive notice and the social problems are briefly but usefully discussed. The

authors rightly emphasize the need for a more positive attitude towards treatment than is now customary.

The last three chapters deal with pathology, the relationship to other demyelinating processes, and the problems of ætiology, and are excellent. Dr. Lumsden's work on the pathogenesis of demyelination is well known and in his description of the anatomy and histology of the disease he writes with a large personal experience, including the detailed examination of the whole nervous system in many cases. It is of interest to learn that in 26 of such examinations 5 failed to confirm a long-standing clinical diagnosis of multiple sclerosis.

While the clinical authors favour the view that the essential ætiologic factor is an allergic state Dr. Lumsden records his observations on the oligodendrocytes and expounds the reasons for his view that they have protective and metabolic functions for the myelin sheaths which are primarily impaired with resulting demyelination. The two views are not incompatible since the oligodendrocytes may be the cells upon which the allergic process in the nervous system is concentrated.

Among the basic problems of this disease is the reason for, and the mechanism of, the extremely slow centrifugal expansion of the plaques. Apparently once a plaque is formed it expands inexorably, for signs of an active process at its periphery are always apparent post mortem. The correlation of this fact with the clinical history of long remissions appears impossible but it has not been shown that the process of expansion in the lesion is a continuous one (especially in the early stages) as the authors imply. It is to be regretted in this connexion that there is no description of the histology of the optic nerve following an attack of retrobulbar neuritis. An expanding plaque in this situation could hardly fail to produce an expanding scotoma in the visual field but such a clinical fact if it ever occurs must be a great rarity. It may well be that the signs of peripheral activity in the lesions is, in many of them, a terminal process, an indication of a terminal failure of the limiting process imposed by resistances put up by the normal tissues.

A special note should be made of the excellence of the illustrations of macroscopic and microscopic material.

References to the literature are very numerous and add much to the value of the book for the student at all stages, who will find nowhere else so full and satisfactory a treatment of multiple sclerosis in all its aspects.

PHILIP CLOAKE.

NERVE INJURIES

Peripheral Nerve Injuries Medical Research Council, 1954. Pp. 451, 276 figs. Price £2 15s.

This volume is the report of the Peripheral Nerve Injuries Committee set up by the Medical Research Council at the beginning of the late war and has been prepared under the editorship of Mr. H. J. Seddon. It is undeniably a dull book and there will be few who will have the fortitude to read it except as a work of reference. Except for those directly concerned with some of the physiological problems involved, the subject of peripheral nerve injuries lacks the variety which provides the fascination of most branches of medicine and surgery. The subject is not made more interesting by being presented as a series of essays by different authors and it may be wondered whether there was really sufficient justification for bringing together under a single cover a series of contributions which have already appeared in much the same form in other journals during the past twelve years.

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As explained in the preface "no attempt has been made to present a systematic account of the diagnosis and treatment of nerve injuries." The work consists of a series of essays on the special aspects of the subject, largely physiological and pathological in nature, by twelve contributors who worked at the different centres for peripheral nerve injuries set up during the early years of the war. Perhaps the most interesting chapter is the one on neurovascular lesions by R. L. Richards, in which is given an excellent account of an important hinterland between the surgery of bones, blood vessels and nerves which is liable, like all border territories, to be an area of neglect and dispute. The chapter on the histopathology of nerve injury by Dr. Blackwood contains a wealth of valuable material and the illustrations are excellent.

The sections on factors influencing functional recovery by Ruth Bowden and on the results of nerve suture by R. B. Zachary contain much detailed information, but suffer from the presence of numerous pages of figures and a style of presentation in numbered paragraphs and sub-paragraphs, which makes them difficult to read. The standard of production and printing throughout is high and the numerous photographs are of excellent quality.

J. ST. C. ELKINGTON.

NEUROPATHOLOGY

Pathologische Anatomie und Histologie des Nervensystems. Edited by Professor W. SCHOLTZ. Part 3. Pp. 1098, 610 figs. Springer: Berlin. 1954. DM. 238.40.

The famous "Henke-Lubarsch" series on special pathological anatomy and histology has at length reached the nervous system with the publication of Volume XIII in 4 parts. Parts 1, 2 and 4 are in prospect later this year. Part 3, now arrived, is composed of three chapters (VI, VII and VIII); the first deals with disturbances attributable to physical factors, the second with parasitic diseases while the third, and bulkiest, part is concerned with tumours. The latter so far is the only section available for review, having been received as a special publisher's excerpt.

Professor Folke Henschen, whose section runs to 627 pages with 421 figs., has performed a remarkable work in reviewing the existing knowledge in this field and in illustrating the whole range of tumours from his extensive personal experience. The appended literature covers 93 pages and extends to the year 1952. The intracranial tumours, including those of the skull and meninges, are first described in order according to their tissue of origin. In dealing with the gliomas considerable space is devoted to general aspects of their pathology, such as their methods of growth and spread, as well as the problems of classification. Nowhere else will the reader find so dispassionate a survey of other workers' views as to how these problems should be terminologically solved. While Henschen's personal classification is based upon that of Bailey and Cushing, it is a simplified form which yet takes account of the modern views concerning anaplastic degradation of the main types without going as far as the over-simplified grading of the Mayo Clinic.

A description of the different types of neuroectodermal, mesenchymal and metastatic tumours of the brain is followed by a special section in which these lesions are treated topographically. The tumours of the spinal cord and its meninges are dealt with in the second part of the chapter.

Professor Henschen must be congratulated not only on his extraordinary industry, but on his wide knowledge of the literature of all countries and his finely-balanced appraisal of the numerous publications of recent years. In common with

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the earlier volumes of this renowned series his contribution will stand as a solid work of reference for all time whatever modifications may be demanded by future research.

DOROTHY RUSSELL.

Fundamentals of Neuropathology. By WILLIAM BROOKS DUBLIN, M.D. Pp. 697, 786 illus. Oxford: Blackwell Scientific Publications; Springfield, Illinois: Charles C. Thomas. 1954. Price £6 13s. 6d.

In style and appearance this is a very pleasant book. It is written from the viewpoint of a general pathologist who is concerned with the routine investigation of neuropathological material. It is written at postgraduate level, is comprehensive and contains considerably more information than is commonly found in the current textbooks of neuropathology in English. The references are almost all American but are so chosen that they themselves refer to the classical literature. Most of the numerous illustrations of microscopical preparations are of paraffin-embedded material. Most of the illustrations of brain slices are of material which was cut at the post-mortem examination, fixed and then photographed without further trimming. It is not a book for beginners, who might, uncritically, believe that frozen sections (especially Sharlach R hæmatoxylin) have no place in the routine examination of neuropathological material, that congenital aneurysms should be grouped among tumours and that rheumatic infection has such prominent cerebral manifestations. But for the informed and critical reader it is very helpful and has many virtues, amongst which should be counted the excellent chapter on inflammatory diseases.

W. BLACKWOOD.

CLINICAL NEUROLOGY

Neurology. By S. A. KINNIER WILSON. Ed. by A. NINIAN BRUCE. Second Edition. Butterworth, London, 1954. 3 vols. Pp. 2060. Price £10 10s.

Kinnier Wilson's "Neurology," when it appeared as an unfinished posthumous work in 1940, was accepted by those who knew him both as his monument and as part of the history of neurology. Dr. Ninian Bruce carried out the difficult task of taking the manuscript through the processes of publication—a task particularly difficult because so much judgment had to be used in assaying the value of disjoined notes, and in presenting incomplete material. Wilson's descriptions of the epilepsies, of degenerative diseases, and of other parts of neurology particularly attractive to him, so reflected his manner and attitude that neurologists were particularly sorry that he had not written the text of the section on aphasia and apraxia, although notes existed.

As well as being such a record of Wilson's work and personality his "Neurology" presented a fairly complete picture of descriptive neurology up to the time of his illness, the interest being directed to clinical syndromes and their morbid anatomical basis. It so happened that Wilson's life was lived in the epoch which saw the fullest development of this form of neurology, and his death prevented him from seeing the enormous growth of chemical and physical achievements which have so altered the study of causation and the methods of treatment of the diseases and syndromes he so fully described. The two large volumes with their prodigious documentation seemed in their truncated form

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to be historical as soon as they were published, for this reason. They made permanent a phase in the study of neurological disease, and in so doing offered an accurate source book to late nineteen and earlier twentieth century literature, particularly that of Germany and France, countries with whose neurology Wilson had a close affinity.

Accepted in this way, criticisms of the work were that it was cumbersome in two heavy volumes, the index was inadequate, and the presentation of the bibliography unorthodox. In the second edition that has appeared now, these objections have been met in full, and there is a much more convenient and efficient source book for investigators. There must be many younger neurologists who have been unable to buy "Kinnier Wilson" who will for this purpose be satisfied with the second edition. They may well think, however, that it would have been wiser to have reprinted the first.

Dr. Ninian Bruce has tried to bring the text up to date, but he accepted an impossible task. Wilson's text was written so largely in the first person, and the present tense, and his text was insusceptible of alteration without destruction. Dr. Bruce has clearly been aware of this, but he has then added sentences to paragraphs, and paragraphs to chapters to bring the text up to date, so that history seems ludicrous. For instance the section on treatment of subacute combined degeneration of the spinal cord, having incorporated a statement about the use of vitamin B_{12} later stages that "More recently, extracts of desiccated hog's stomach have been used with great benefit. In the form of a powder, mixed with chocolate or milk and drunk immediately, or combined with a savoury or potted with cold meat———. Some of the more elegant stomach extracts are expensive, but cheaper and equally reliable brands cost less than half a pound of liver." Similarly, although the use of antibiotics and sulphonamides are of course included in the treatment of pyogenic meningitis, there are such incredible statements as "specific immune sera are at our disposal for some bacterial strains, and should be applied in as close contact as possible with the inflamed meninges; intrathecal is superior to intravenous or subcutaneous techniques. This is the method *par excellence* for the meningococcal and for differing pyogenic types." There are long descriptions of washing through the subarachnoid space, continuous drainage of cerebrospinal fluid, and other discarded forms of treatment cheek by jowl with sentences such as "There is no evidence that systemic penicillin can cure meningitis," and "No resistance to penicillin has yet been found," or "Penicillin is sensitive to the meningococcus,"—additions which do great harm to Wilson's original work.

In short, this second edition is a work for the expert neurologist who can sift and discard the less critical contemporary additions and the out-dated views, from the timeless description of unchanged fact.

The second edition is best in the untouched descriptions of disease, such as that of chorea, and the addition of a note on disturbance of copper metabolism in hepato-lenticular degeneration and the treatment by B.A.L. of what Wilson used to refer to as "my disease" shows how rapidly neurology has advanced since the first edition. But if it has advanced it seems ludicrous in a work which is not a reprint to leave myasthenia gravis and migraine in the section of volume 3 devoted to "Disease conditions of uncertain nature." Equally in this age of biochemistry it is surely unwise to confine the section on metabolic disease to subacute combined degeneration, pellagra and beri beri.

A new chapter on aphasia, apraxia and agnosia by Russell Brain fits well into the framework of Wilson's text and would have been in keeping with the first edition.

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The final chapters, dealing with "The Neuroses" should be read as they were written, for as Wilson wrote, "current neurological opinion takes the word to signify a disorder of nervous function for which, as yet, no underlying basis has been found." In his time there was a sharp distinction between a neurosis and a psychoneurosis, and by occupational neurosis was meant writer's cramp, and allied conditions. It is alteration of meaning of this sort, as well as major changes in attitudes and amazing increases in knowledge that have made Dr. Ninian Bruce's aim to present Kinnier Wilson in modern dress impossible and the result unfortunate.

DENIS WILLIAMS.

DISORDERS OF MEMORY

Zur Psychologie und Psychopathologie der Erinnerungen. By Dr. HANS HEINRICH WIECK. Georg Thieme Verlag. Stuttgart. 1955. Pp. 118. Price DM. 9.60.

This book was submitted as an academic thesis to the Medical Faculty of the University of Cologne. It is an interesting contribution to the psychology and psychopathology of memory, but its rather ponderous style and difficult terminology make for somewhat confusing reading.

The author's approach is in the main phenomenological, which is a point of view better understood and appreciated in Germany than in this country. Nevertheless, the familiar categories of impression, repetition, recall and recognition are still to be discerned. In the last analysis, memory is for Dr. Wieck a philosophical problem—a "metaphysical postulate."

The bibliography is large, but mostly limited to German references. For example, there is no mention of Wilder Penfield's work, nor that of Mackay; nor is there any reference to cybernetics.

E. B. STRAUSS.

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